THE UNIVERSITY OF ALBERTA

SYNTHESIS OF ENDO-5-FORMYL-2-OXABICYCLO[2.2.2] OCT-7-ENE-3-ONE AND DERIVATIVES

by

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A THESIS

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TO MY SUCCESSORS

THE UNIVERSITY OF ALBERTA

FACULTY OF GRADUATE STUDIES AND RESEARCH

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research, for acceptance, a thesis entitled SYNTHESIS OF ENDO-5-FORMYL-2-OXABICYCLO[2.2.2]OCT-7-ENE-3-ONE AND DERIVATIVES submitted by COLIN COOMBES in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

A synthetic scheme was devised to prepare 5-methylene-2-oxabicyclo[2.2.2]oct-7-en-3-one, XVI. The decarboxylation of this compound should give the alicyclic isomer of toluene, 5-methylene-1,3-cyclohexadiene, X. Compound X was required for use as a model initiator for the polymerisation of styrene. endo-5-Formyl-2-oxabicyclo [2.2.2]oct-7-en-3-one, XIII, was prepared by the Diels-Alder reaction of α-pyrone and acrolein. Reduction of XIII gave the corresponding alcohol, XIV, the structure of which was proved by n.m.r. spectroscopy and chemical conversion to a compound of known configuration. The tosylate of XIV was a stable solid which could not be converted to the required diene XVI.

A similar synthetic scheme was used to prepare the tosylate of endo-5-(1-hydroxyethyl)-2-oxabicyclo [2.2.2]oct-7-en-3-one. This secondary tosylate, XXVII, underwent an elimination reaction to give a mixture of products, A. The gas-liquid chromatogram of A showed peaks due to ethylbenzene and styrene. The ethylbenzene is thought to arise from the decarboxylation and subsequent rearrangement of 5-ethylidene-2-oxabicyclo[2.2.2]oct-7-en-3-one, XXVIII, in the injection port. This indicates that XXVIII was formed by the elimination reaction of XXVII.

Decarboxylation of XXVIII should give 5-ethylidene-1,3-cyclohexadiene, XVII, a compound with similar structural features to X. XVII should be equally as useful a model initiator as X. XVII was prepared in situe from A in the presence of monomeric styrene at 100°C. Its effect on the polymerisation of styrene was measured. An increase in the polymer formed of 3.5% per hour, at 100°C, was found for this initiated polymerisation over the thermal polymerisation of styrene at 100°C.

Appropriate kinetic data on decarboxylation of XIV and A were also measured.

ACKNOWLEDGEMENTS

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INTRODUCTION

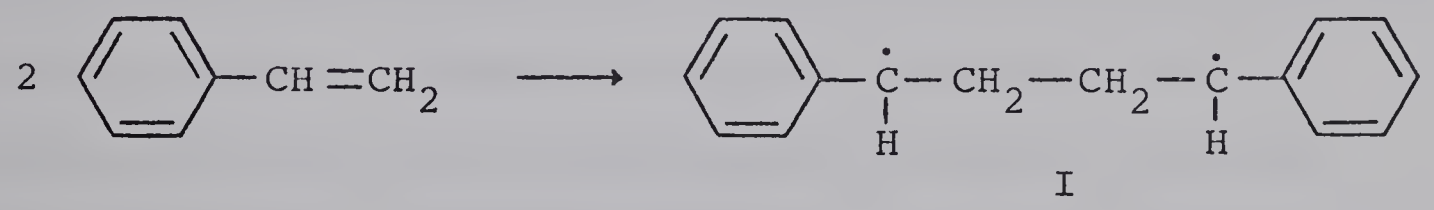
It appears from the researches of Warner (1) that styrene was first discovered by Neuman previous to 1786. The compound was not named, however, until 1839 by Simon (2) who found that styrene was transformed, upon standing for several months, into a jelly-like material. This material was presumably the metastyrene made by Berthelot (3) who coined the term polymerisation. Staudinger (4) later (1935) renamed the material polystyrene.

The first systematic kinetic investigation of the uncatalysed polymerisation of styrene was carried out by Breitenbach and Rudorfer (5). Their results indicated that the reaction was second-order, with respect to monomer concentration, in dilute solution using various solvents. First-order dependance was found for bulk polymerisation (pure monomer). Walling, Briggs and Mayo (6) later found that the experimental results for bulk polymerisation were in reasonably good accordance with second-order dependance if the monomer concentration was replaced by its thermodynamic activity, as estimated from vapour pressure measurements. Inhibition (7) of the thermal polymerisation of styrene by substances such as quinones, amino and nitro compounds, which are considered to be radical scavengers, shows this reaction proceeds through a radical mechanism as in the case of radical initiated

styrene polymerisations (8a,b). Convincing evidence that the thermal polymerisation of styrene is not initiated by adventitious impurities is given by the reproducibility of the rates of this reaction found by various workers (6, 9a,b,c).

In the light of the kinetic evidence then available, Flory (10) suggested, in 1937, that two styrene molecules can couple to form a diradical eq [1].

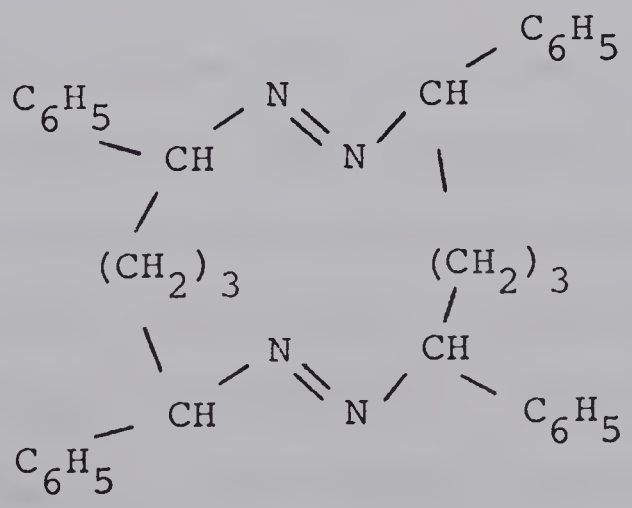
[1]



I

This is compatible with second-order kinetics and also the formation of such a diradical is energetically feasible (ΔH = 29 Kcal/mole). The observation of Melville and Watson (11) that the behaviour of quinone inhibitors differs in the thermal polymerisation of styrene from that in the initiated polymerisation of styrene, which involves monoradicals, seemed to support Flory's mechanism. Russell and Tobolsky (12) assumed that diradicals were formed in the thermal polymerisation, most of which self-terminate to form small rings. This assumption was based on the observation that the rate of initiation measured by the consumption of the inhibitor diphenylpicrylhydrazyl (DPPH) is very much greater than that calculated from the rate

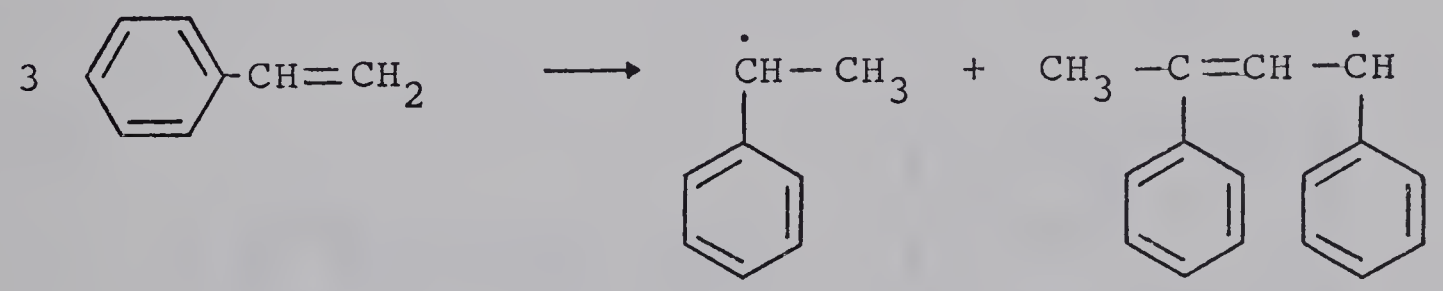
of polymerisation and the known overall rate coefficients. In the initiated polymerisation the two values agree. The diradicals were assumed to react with the DPPH in the presence of this inhibitor. It was predicted by Haward (13), from statistical calculations, that mutual termination of the ends of a long chain diradical would be expected to be very much greater than termination involving radicals of different chains. Zimm and Bragg (14) showed, using known termination and chain transfer constants, that diradicals cannot grow large enough to give high molecular weight polymer. Attempts to collect evidence for or against the diradical mechanism were directed towards the use of model compounds which can generate diradicals as potential initiators. Russell and Tobolsky (15) found the polymerisation of styrene was not appreciably initiated by cyclic disulphides, which yield diradicals photochemically. Cyclic bis-azo compounds of the type:



were found (16) to be very inefficient initiators. 3,6-Diphenyl-3,4,5,6-tetrahydropyridazine, which yields the 1,4-diphenylbuta-1,4-diyl radical (17), I, was reported to initiate styrene polymerisation giving a kinetic chain length of only 8-10 monomer units (18). Further evidence against the formation of a diradical is found in the lack of deuterium isotope effect observed by Hammond and Kopecky (19) in the polymerisation of β,β-dideuteriosty-rene.

After a careful study of the kinetics of the thermal polymerisation of styrene in bromobenzene, in which he observed overall kinetics of five-halves-order, Mayo (20) proposed a termolecular initiation step eq [2].

[2]

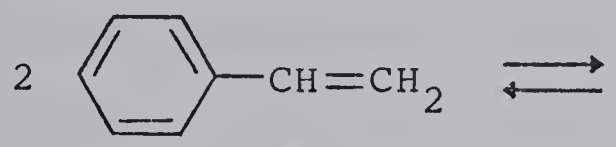


The work of Hiatt and Bartlett (21) gave excellent support to Mayo's (20) findings. They suggested the reversible formation of an association product of two molecules of styrene, which then reacts with a third molecule to yield monoradicals. Three possibilities for the nature of the association product are put forward by the above authors; (i) Flory's diradical, I, with the condition that it is formed reversibly eq [3], (ii) a Diels-Alder addition

product, II eq [4] (suggested by Mayo (22)), and (iii) a charge transfer complex, III eq [5]. Any of these three species might react with the third molecule of styrene to yield monoradicals eqs [6]-[8].

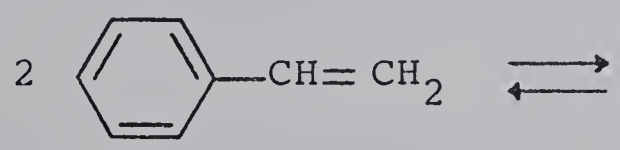
Evidence against the formation of a diradical species has already been presented.

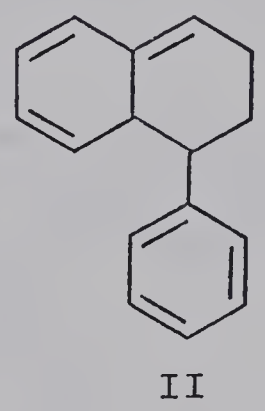
[3]



I

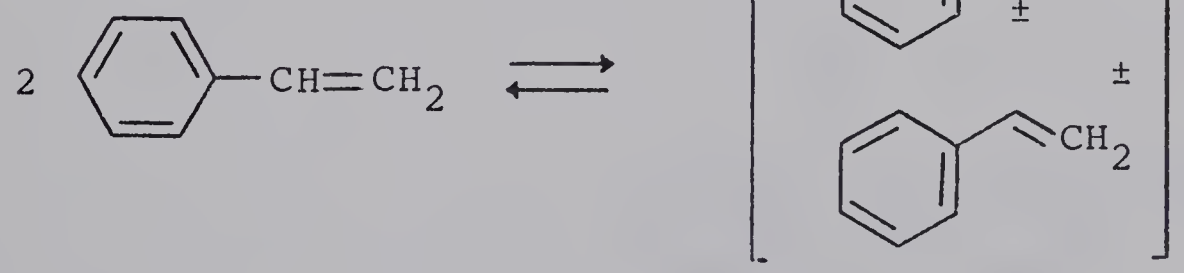
[4]





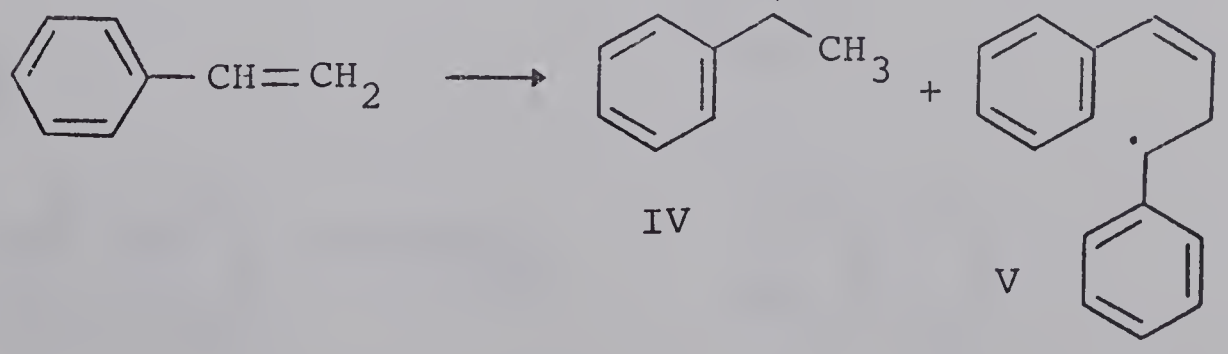
II

[5]



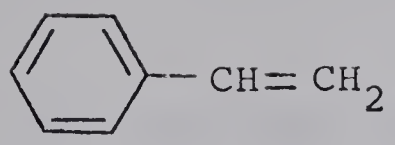
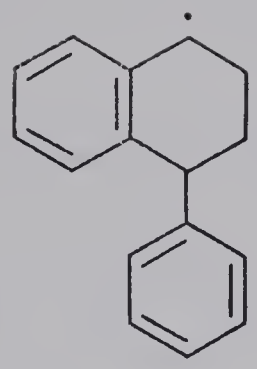
III

[6]

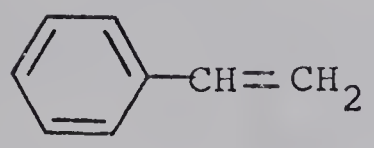


IV

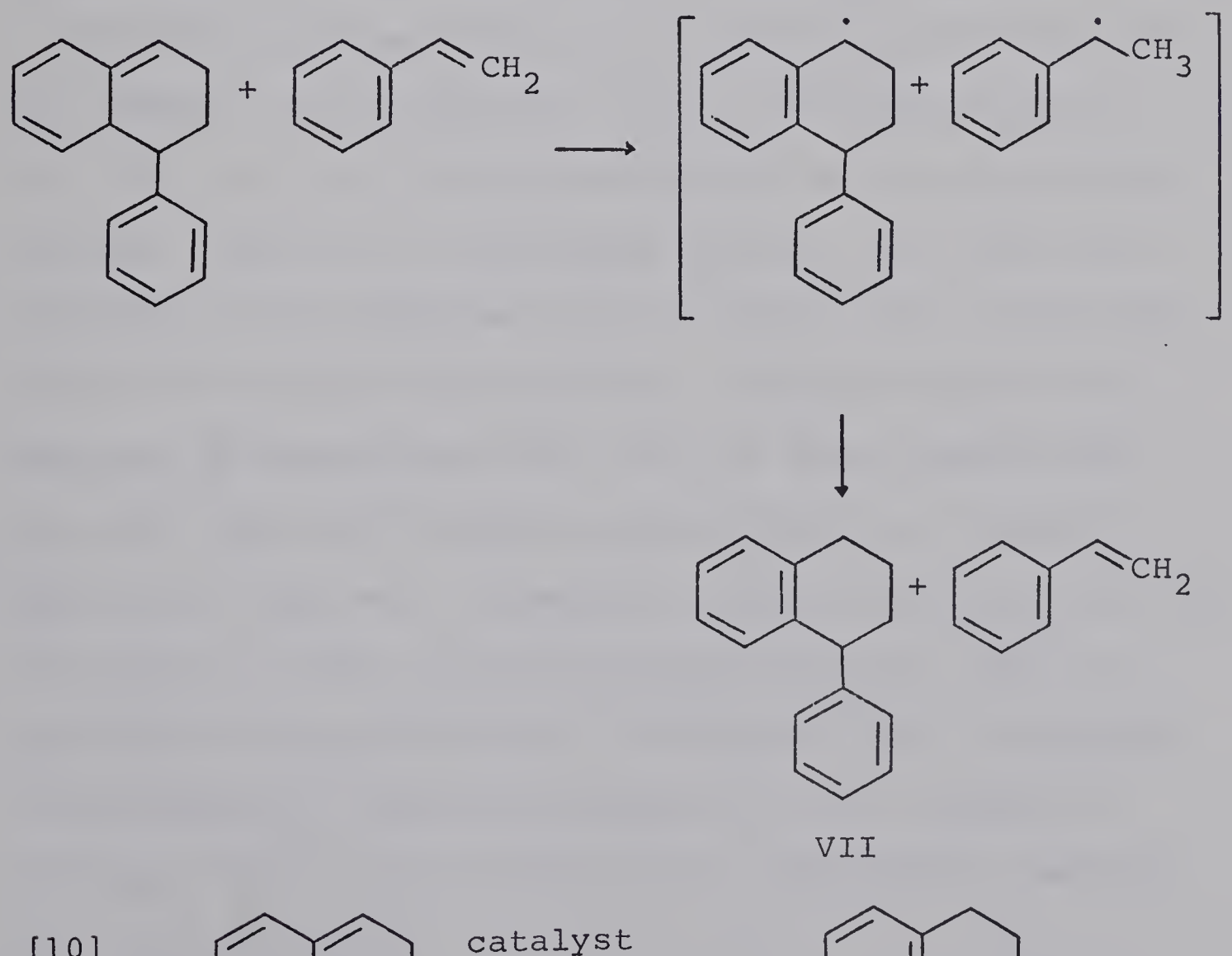
V

[7] II +  ⟶ IV + 

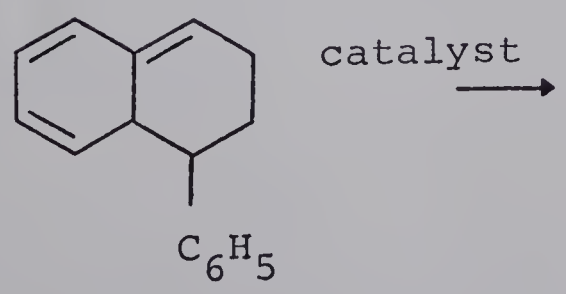
VI

[8] III +  ⟶ IV + V or VI

The isolation of 1-phenyltetralin, VII from both inhibited (23) and uninhibited (22, 24-27) thermal polymerisation lends support to the formation of II (see eqs [9] and [10]). The trimer formed by the combination of IV and VI

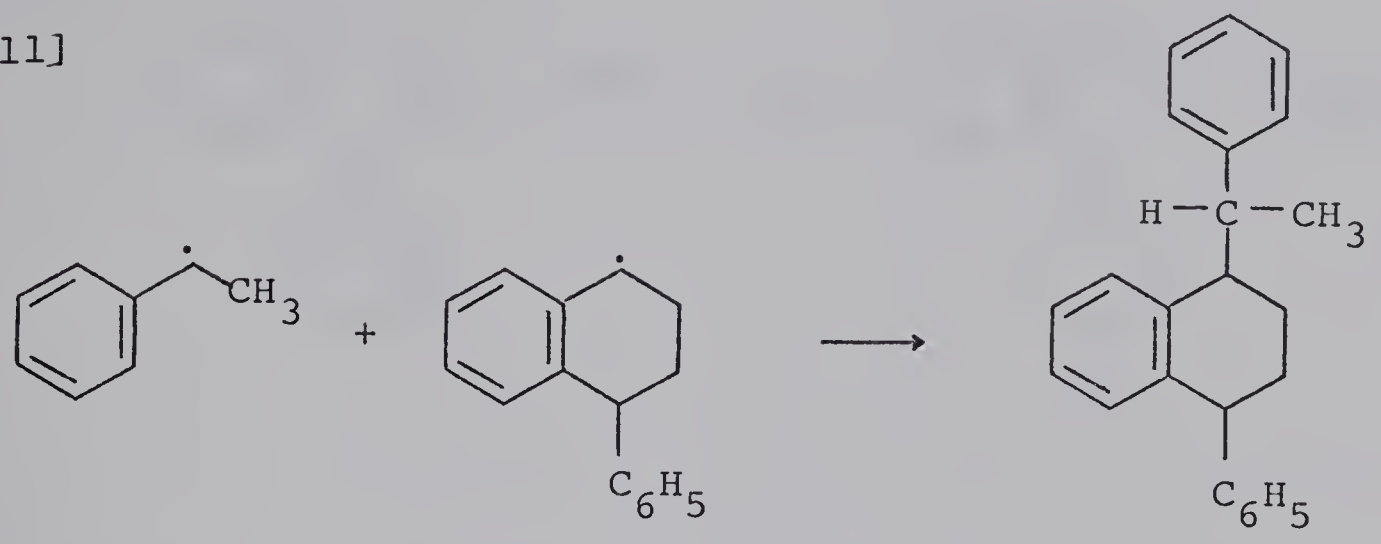
[9] 

VII

[10] 

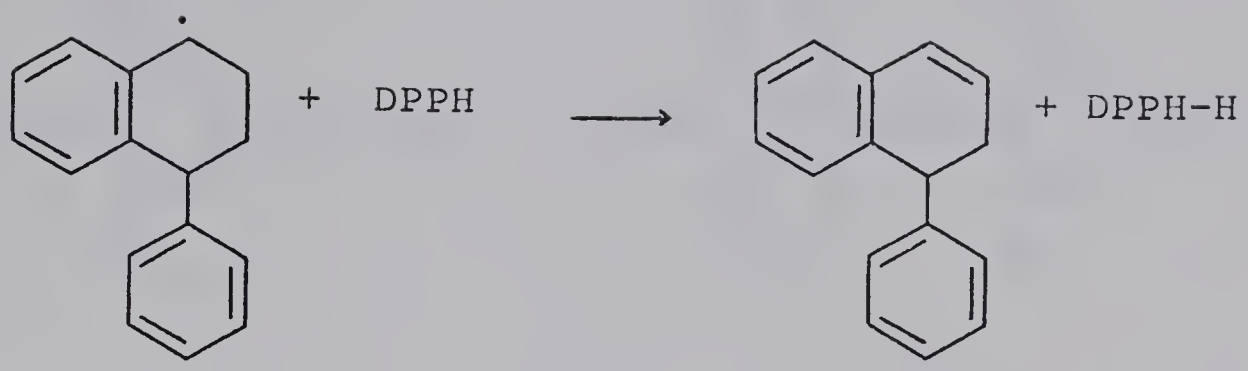
has also been isolated (24) eq [11]. The kinetic studies

[11]



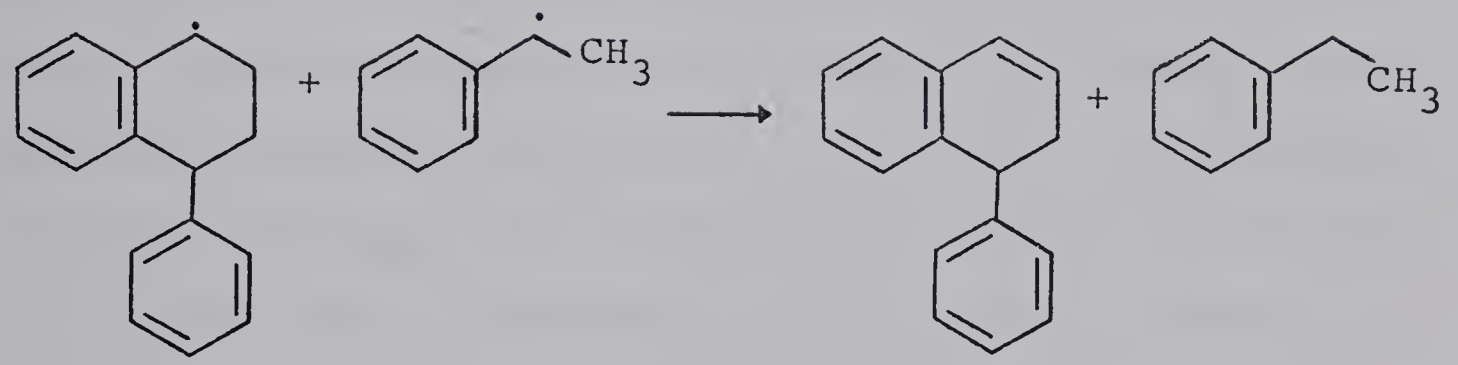
on deuterated styrenes by Kopecky and Evani (28) also support a mechanism involving the initial formation of II. A deuterium isotope effect on the rate of initiation of the thermal polymerisation, k_{iH}/k_{iD}, was calculated to be 1.80 ± 0.31 for the polymerisation of 2,6-dideuterio-styrene. This is in accordance with eq [7] where the transfer of the hydrogen atom at C-9 (C-2 or C-6 of styrene) of II is rate determining. Further evidence is supplied by Kopecky and Hall (29) in their studies of the DPPH inhibited thermal polymerisation of styrene. They found that more 1-phenyl-1,2-dihydronaphthalene, VIII, was formed in DPPH inhibited polymerisations than in uninhibited polymerisations. Compound VIII is believed to be formed by disproportionation of the 4-phenyl-1-tetralyl radical with DPPH or the 1-phenylethyl radical, eqs [12] and [13].

[12]



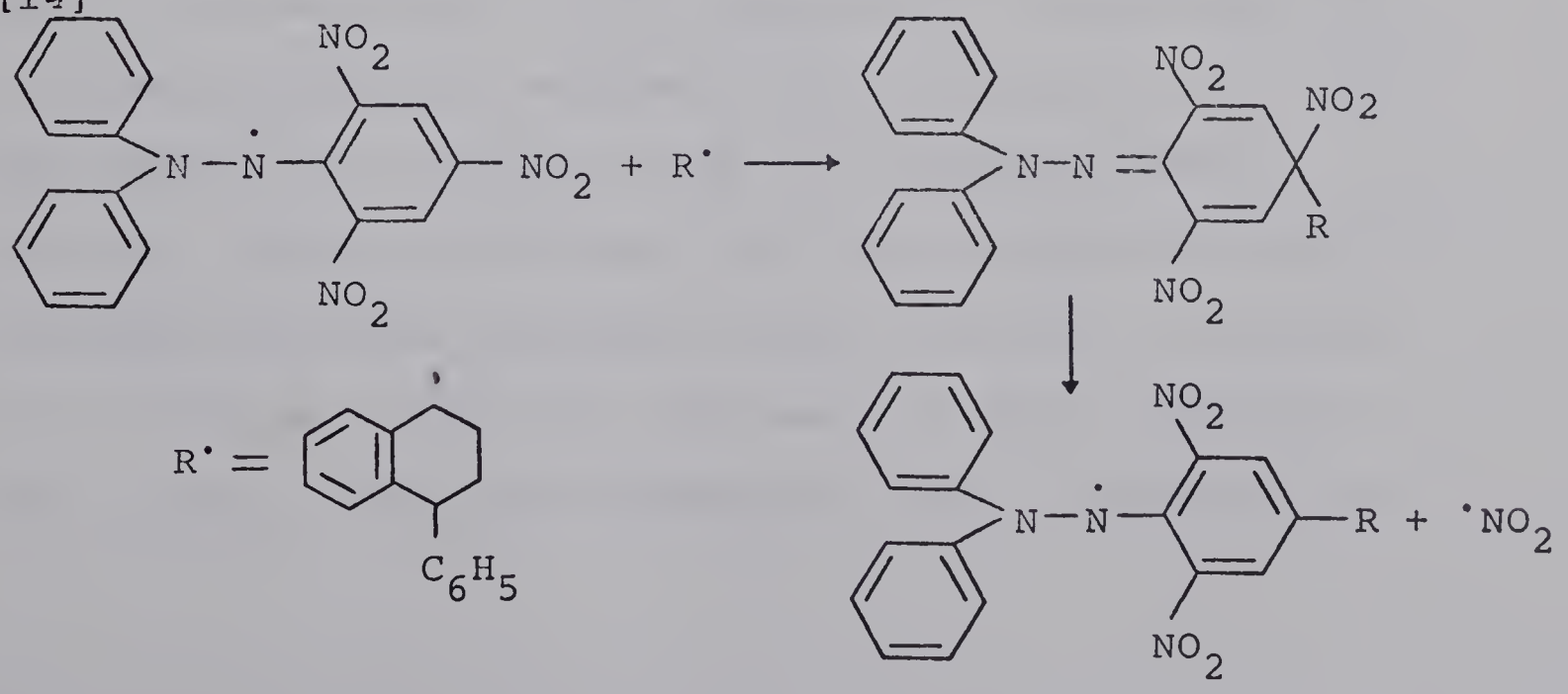
VIII

[13]

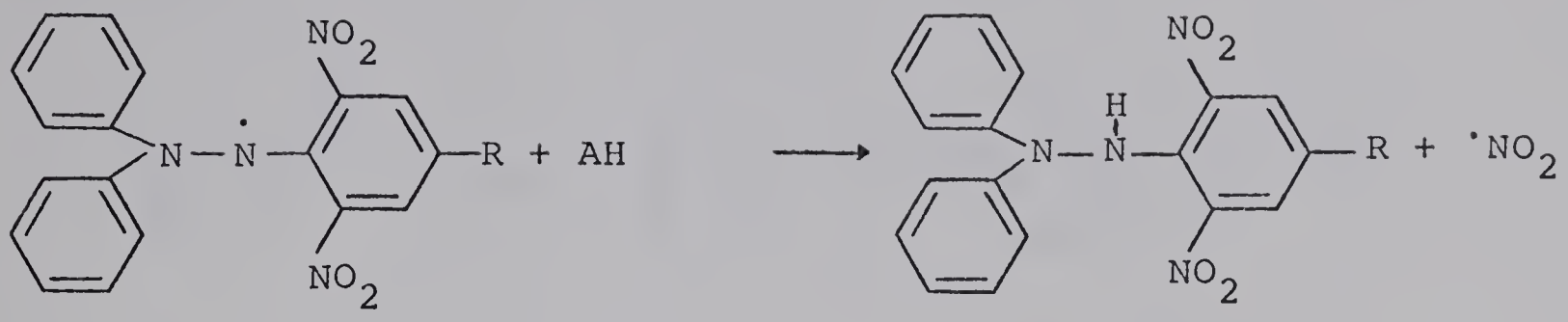


1,1-Diphenyl-2-(2,6-dinitro-4-(4-phenyl-1-tetralyl)-phenyl)-hydrazine, IX, was also isolated from their reaction mixtures. Compound IX is thought to be formed in the following manner, eqs [14] and [15].

[14]

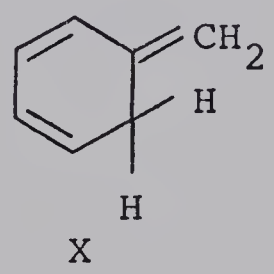


[15]



IX

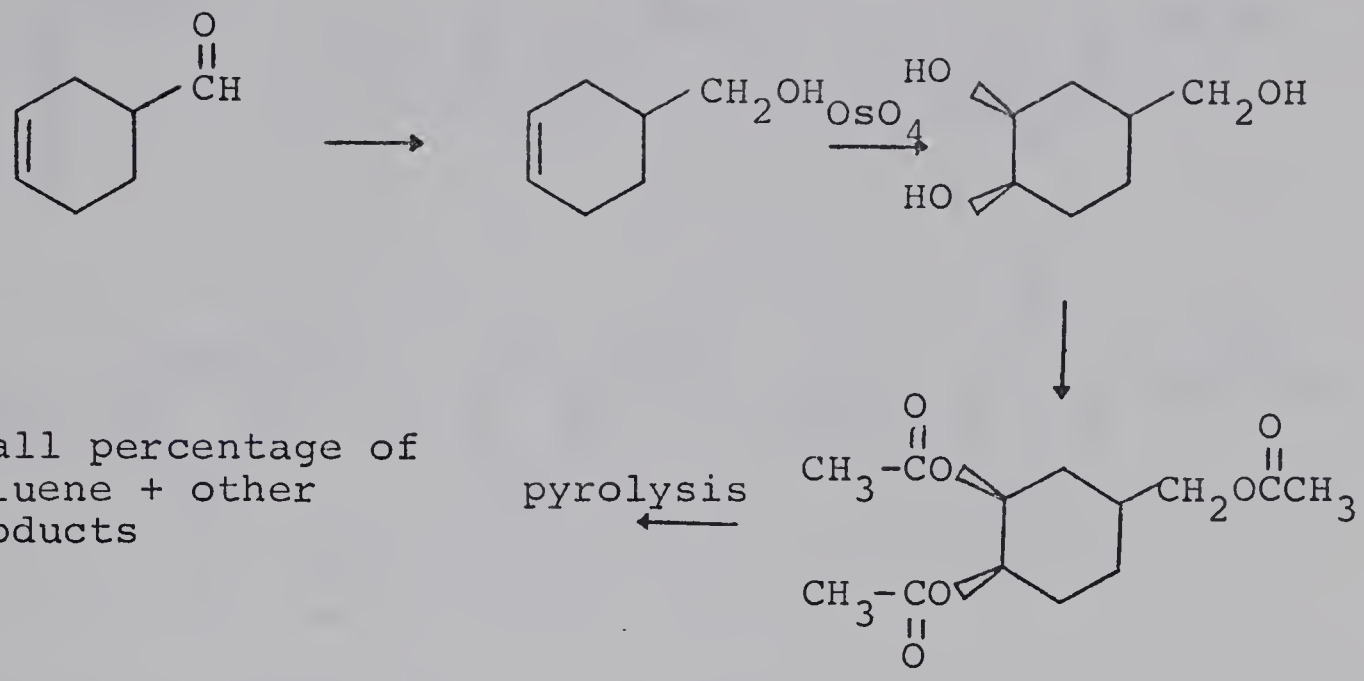
The examination of the efficiences of species like II as initiators in the polymerisation of styrene could further substantiate the evidence in favour of the mechanism represented by eqs [4] and [7]. 5-Methylene-1,3-cyclohexadiene, X, is chosen as a model compound for II, having similar structural and reactivity features as II.



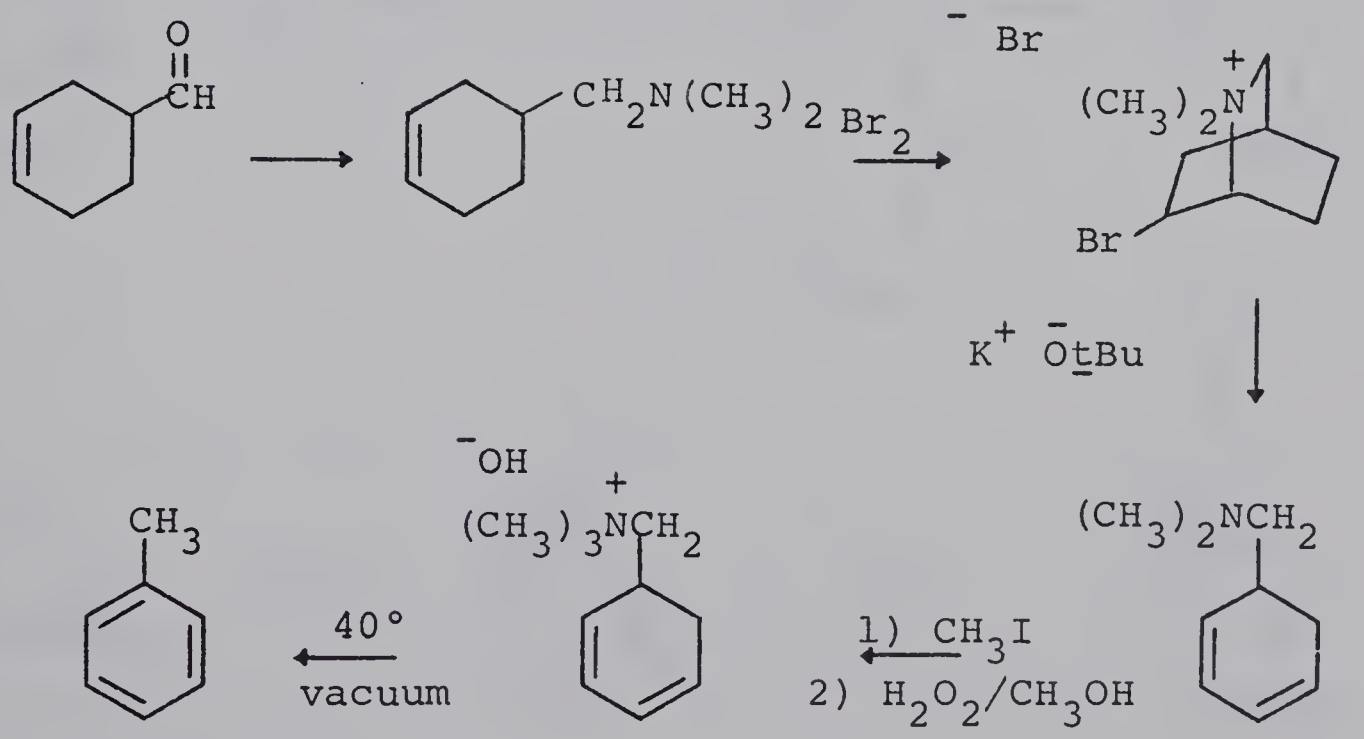
X

The compound X has been previously reported by Bailey and Baylouny (30) as the product of pyrolysis of 1,4-cyclohexadiene-1-methanol methyl carbonate, XI. It was formed in a 1:9 ratio with its aromatic isomer, toluene. Kopecky and Evani (31) have attempted to synthesise X by three different routes in order to isolate it in a form suitable for its use as a model initiator. Two attempts, outlined in Schemes I and II, resulted in

SCHEME I

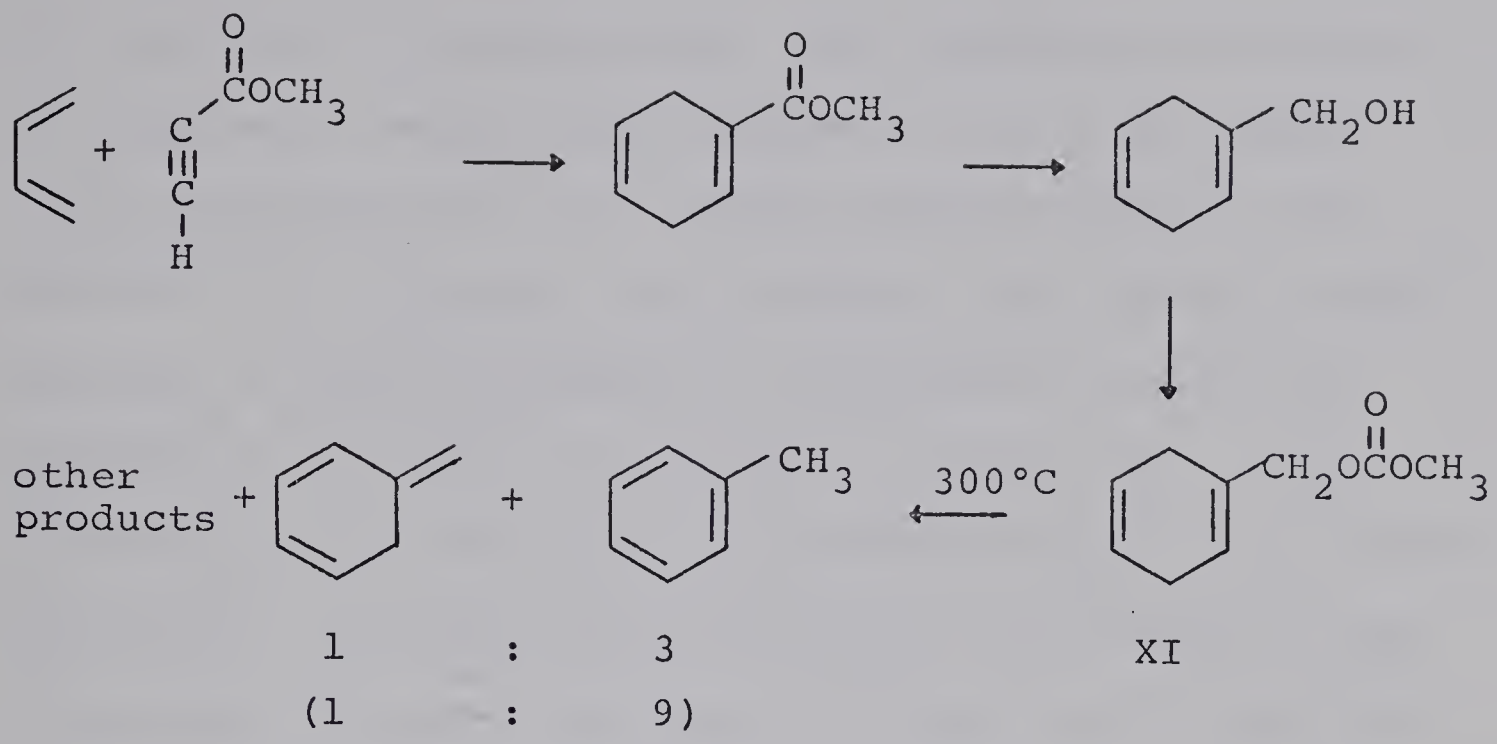


SCHEME II



isolated in
cold trap at
-78°C

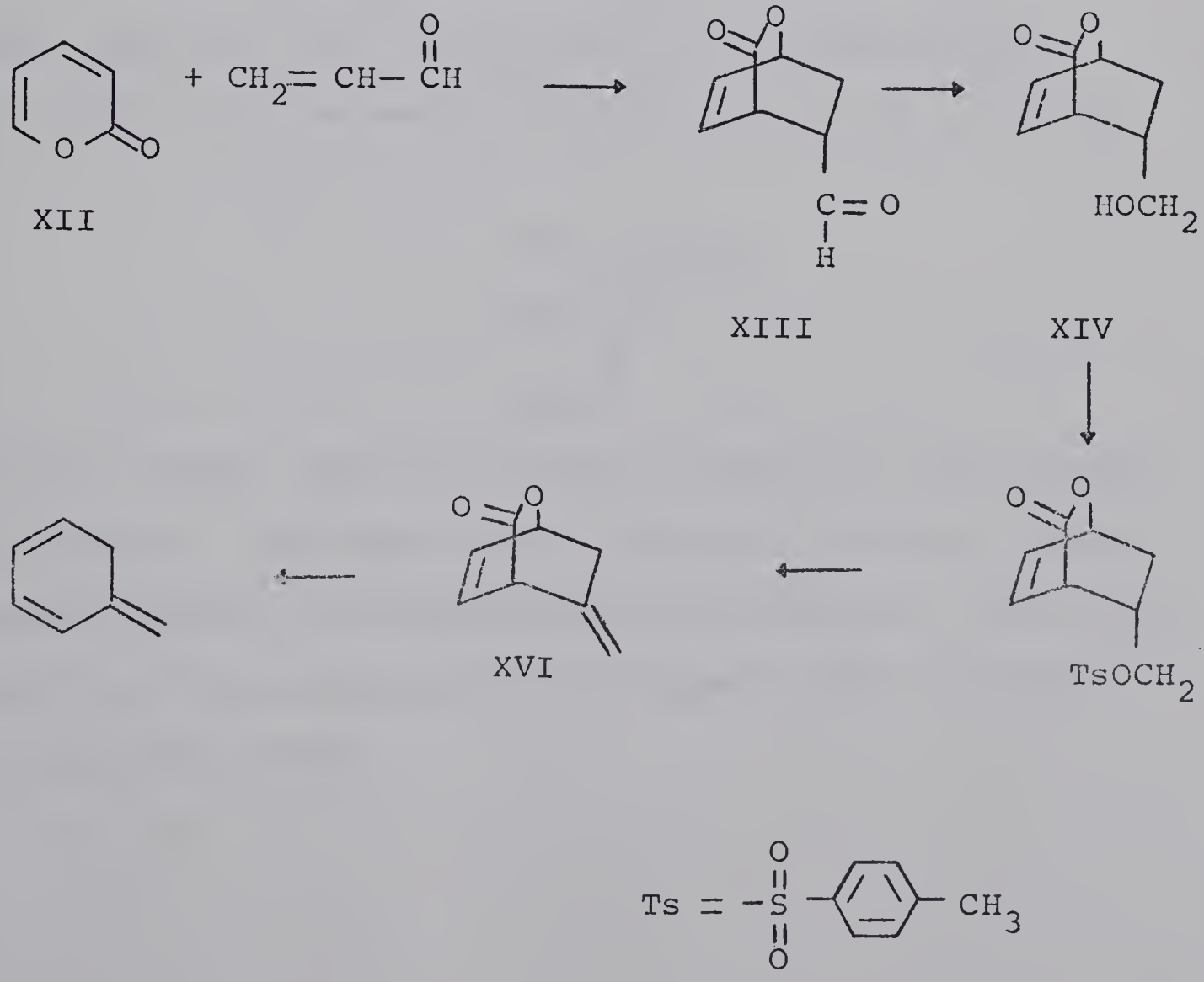
SCHEME III



(1 : 9)

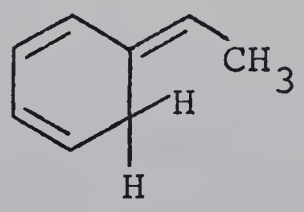
Bailey and Baylouny's result in ( ).

SCHEME IV



the isolation of toluene only. The repetition of Bailey and Baylouny's method (30), Scheme III, did not result in the isolation of X in a useful form although it was produced in a 1:3 ratio with toluene. The present investigation is another attempt to synthesise X using the sequence of reactions as outlined in Scheme IV. (The structures are drawn with the aforeknowledge of the stereochemistry.) Although this attempt was unsuccessful some interesting chemistry has been developed and is reported. The chemistry studied does in fact point to methods which may be useful for the synthesis of X.

During the course of the investigation it became apparent that 5-ethylidene-1,3-cyclohexadiene, XVII, might be more easily obtained than X, by a similar



XVII

synthetic route. This has closer structural similarities to II than X. Evidence for the formation of XVII is presented although the compound was not isolated. The effect of XVII on the polymerisation of styrene also has been investigated briefly.

RESULTS

α-Pyrone XII

The starting material, α-pyrone, for Scheme IV was prepared by the method of Zimmerman, Grunewald and Paufler (32) by the pyrolysis of coumalic acid at 650°C in 60-87% yield. The only modification made to their method was that the coumalic acid was not recrystallised before the pyrolysis. This did not seem to adversely affect the yield of α-pyrone. Although coumalic acid is commercially available it is readily and more economically prepared from d,l-malic acid. The method of Wiley and Smith (33) was used to prepare this material in crude yields of up to 80%, by the treatment of d,l-malic acid with fuming sulphuric acid.

The Diels-Alder Adduct of α-Pyrone and Acrolein--endo-5-Formyl-2-oxabicyclo[2.2.2]oct-7-en-3-one, XIII

The Diels-Alder reaction between excess acrolein and α-pyrone was conveniently carried out without any solvent as both the reactants are mobile liquids. At room temperature the reaction was found to be very slow, for practical purposes non-existant. After 72 h no product was detectable by thin layer chromatography (t.l.c.). At 60°C, however, product was detected after 1 h. Heating

for 120 h gave up to 69% yields of adduct. The yields are based on starting α-pyrone, assuming that all the acrolein consumed during the course of the reaction formed adduct. This assumption is necessary as the adduct could not be purified. All the unreacted α-pyrone could not be removed from the adduct even by heating the product mixture at 60°C under a reduced pressure of 15 μ for 12 h. Attempts at crystallisation of the adduct failed. Distillation and column chromatography resulted in decomposition of XIII. The n.m.r. spectrum of the product, with the excess acrolein and most of the unreacted α-pyrone removed, shows three absorption peaks in the aldehydic proton absorption region (τ = 0-1). The relative intensity of one of the absorption peaks is 6.7 times as large as the sum of the intensities of the other two absorption peaks. This seems to indicate that mainly one of the four possible isomers of the adduct has been formed. Absorption peaks also are seen in the olefinic (τ = 3.6) and bridgehead proton (τ = 4.75 and 6.1) absorption regions, as would be expected for the adduct XIII.

The n.m.r. spectrum of the product of distillation of the crude adduct at 100°C and 0.1 mm shows the adduct to have decomposed. The n.m.r. absorption peaks of benzaldehyde (34) are clearly discernible in this spectrum. The rest of the absorption peaks are in the

aldehydic, olefinic and allylic proton absorption regions. These could be due to isomers of dihydrobenzaldehyde. No further studies on these decomposition products were made.

Attempts at increasing the rate of reaction by catalysis (35,36) were unsuccessful, see Table I. The only products obtained were insoluble, polymeric materials.

Reduction of XIII to endo-5-Hydroxymethyl-2-oxabicyclo [2.2.2]oct-7-en-3-one, XIV

Several unsuccessful attempts at the reduction of XIII were made using such reagents as: sodium borohydride, in basic solution (37); pyridine-borane (38); and a selective hydrogenation catalyst, platinum oxide/ ferrous chloride/zinc acetate (39). The method of Wendler, Graber and Hazen (40), i.e. sodium borohydride in methanol-tetrahydrofuran (THF), was successfully employed for the reduction. This was somewhat inconvenient due to the large quantities of solvent required, however. This reaction was found to be sensitive to concentration effects. The required product was no longer obtained if the concentration of the reactants was increased to 2.5 times that used in the original method. It was found, however, that the overall concentration of the reactants could be increased by 3 times if the reaction was cooled in ice and the sodium borohydride slowly added as a suspension with the solvent (see Experimental

TABLE I

Catalysis of Diels-Alder Reactions

CATALYST	SOLVENT	TEMP, °C	RXN. TIME (h)	PRODUCT
zinc chloride	CH_2Cl_2	39	72	starting material
stannic chloride	benzene	60	2.5	brown solid
stannic chloride	benzene	25	16	yellow solid
boron trifluoride etherate	benzene	25	19	brown solid

section).

The product of reduction was a brown oil from which a white solid crystallised on standing for 1-2 days. The n.m.r. and i.r. spectra and chemical analysis of the white solid are consistent with the proposed structure. The melt of this solid was seen to evolve gas at 95°C, a few degrees above its melting point. The residual brown oil showed a very similar n.m.r. spectrum to that of the white solid. In most cases absorption peaks due to α-pyrone and a few absorption peaks of unknown origin can be seen in the spectra of the oil. All attempts to further crystallise the oil or to further purify it were unsuccessful.

Structure Determination of XIV

There are four possible structures for the Diels-Alder adduct XIII. Considering the rules for Diels-Alder addition as outlined by March (41), it would be expected that the structure shown below would predominate. All the derivatives of XIII should have the same basic structure as the reactions carried out on the system (except for the elimination reactions) are unlikely to affect the stereochemistry of C-5. It was convenient to study the alcohol XIV for the purposes of structural determination as it was obtainable in a pure form. It should be noted that

the structure shown is one enantiomer of a pair and that its mirror image would be expected to be formed in exactly the same proportion. No attempt was made to separate these enantiomers.

A series of 100 Mc n.m.r. spectra, with spin-decoupling, were taken of compound XIV. The results are tabulated below (Table II).

TABLE II

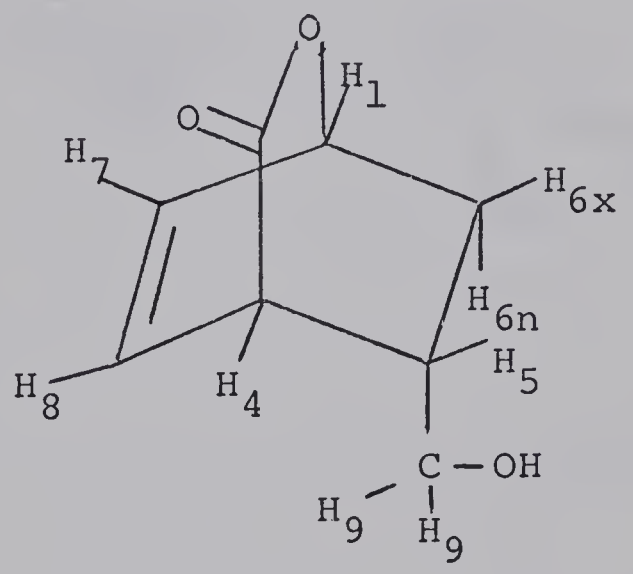
Spin-decoupled N.m.r. Spectra of XIV, in $CDCl_3$

DOUBLE IRRADIATION AT (τ)	SIMPLIFICATION OF SPECTRUM AT (τ)
4.80	8.85, 7.70 and 3.50
6.36	7.70 and 3.50 (6.68)
6.68	7.70 (6.36)
7.70	6.68 and 4.80
3.50	6.36 and 4.80

Values in parentheses indicate protons which cannot be observed due to their proximity to the centre of irradiation.

The spin-decoupled n.m.r. spectra clearly point to the proposed structure as being correct, with the

limitation that no information is available as to whether the hydroxymethyl group is endo or exo. The only assumption that has to be made, in analysing the spectra, is that H-1 will absorb at lower field (lower τ value) than H-4. This is a reasonable assumption as the literature shows that, in general, protons attached to carbons adjacent to oxa groups resonate at lower field than do those attached to carbons adjacent to keto groups.

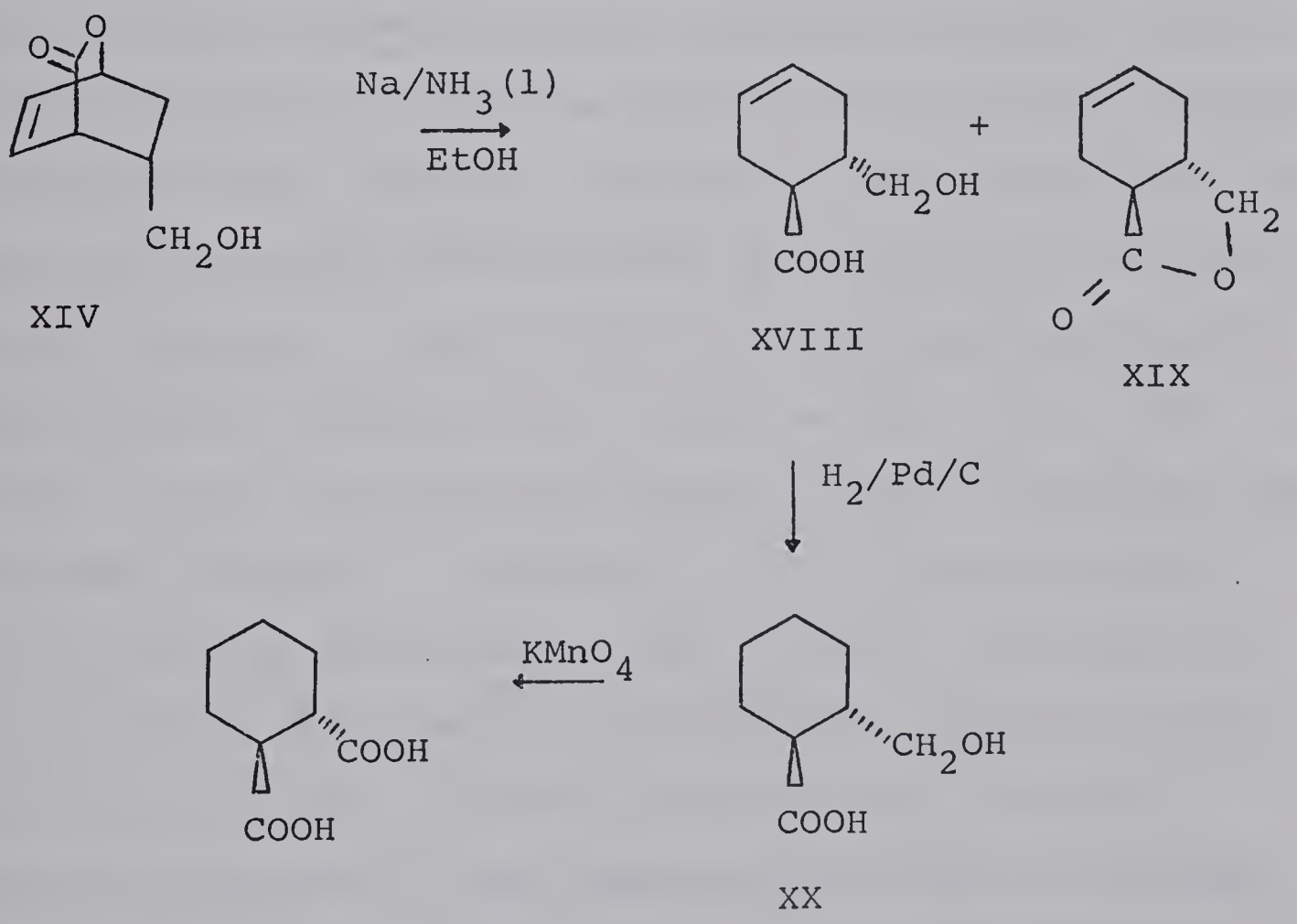


The protons have been assigned as follows: H-1 τ 4.80, H-4 τ 6.36, H-5 τ 7.70, H-6n τ 8.85, H-6x τ 7.70, H-7 τ 3.50, H-8 τ 3.50 and H-9 τ 6.68. The coupling constants (Hz) measured were: $\underline{J}_{16n}$ 1, $\underline{J}_{16x}$ 3, $\underline{J}_{17}$ 5, $\underline{J}_{45}$ 2, $\underline{J}_{48}$ 6, $\underline{J}_{47}$ 2, ($\underline{J}_{6n6x}$ 17 ± 1, J_{6x5} 8, J_{6n5} 8) The accuracy of the coupling constants in parentheses is in some doubt due to difficulty in measurement caused by the overlapping of the absorption peaks of H-5 and H-6x. The assignment of H-6n is made by analogy to similar nonbornene systems (42). The endo H-6 proton is shielded by the

π-bond between C-7 and C-8 which causes it to resonate at high field. This effect is increased by eclipsing of H-6n by a methylene group, i.e., C-9.

It was desirable to have chemical proof of the structure of XIV, especially with regard to the stereochemistry of C-5. Scheme V was devised to provide this

SCHEME V



XIV

XVIII

XIX

XX

proof. (The structures are drawn with the aforeknowledge of the result.) If XIV does in fact have the structure proposed then trans-1,2-cyclohexanedicarboxylic acid should be the end product of this scheme of reactions. This was found to be the case. The other three possible

isomers of XIV would give cis-1,2-, cis-1,3- and trans-1,3-cyclohexanedicarboxylic acids. None of these isomers of cyclohexanedicarboxylic acid were isolated.

The metal reduction (43) was carried out on the solid alcohol XIV. Compounds XVIII and XIX were obtained in 64% and 15% yields, respectively. The n.m.r. spectrum of XVIII shows absorption peaks in the expected regions, i.e. olefinic and ring proton absorption regions, but is not "clean" enough to eliminate the presence of other possible isomers of this compound. The n.m.r. spectrum of the lactone XIX is readily rationalised as being due to the proposed structure. The oil XVIII was hydrogenated over 5% palladium on charcoal (44) to give another oil in 98% yield. Only 71% of the theoretical volume of hydrogen was consumed, however. A portion of this oil was oxidised with potassium permanganate (45) to give a 66% yield of an off-white solid melting at 195-203°C. Recrystallisation of this solid yielded a material with a melting point of 228-230°C. This compound was shown to be trans-1,2-cyclohexanedicarboxylic acid by a mixed melting point with the authentic material.

p-Toluenesulphonate (XV) of XIV

Schleyer's method (46) was found to be quite satisfactory for the conversion of XIV to the tosylate XV.

Treatment of solid XIV with p-toluenesulphonyl chloride in pyridine gave XV, which was a white crystalline solid, in quantitative yields. From the oil XIV only a low yield of solid tosylate XV could be obtained plus a brown oil. The brown oily tosylate had a similar n.m.r. spectrum to that of the white solid. Subsequent reactions on the tosylate were carried out on the solid material. The n.m.r. spectrum of the tosylate XV shows the expected absorption peaks in the aromatic, olefinic, bridge-head and methyl proton absorption regions. This compound also decomposes at its melting point, 96°C.

endo-5-Chloromethyl-2-oxabicyclo[2.2.2]oct-7-en-3-one, XXI

The solid alcohol XIV was converted to the chloride, XXI, using thionyl chloride by a modification of Darzens' method (47) due to Frazer, et al. (48), in 60% yield. This material was also a white crystalline solid.

Conversion of Tosylate XV to the Corresponding Bromide and Iodide

Attempts to convert XV to the bromide using sodium bromide in DMSO, and to the iodide using sodium iodide in acetone by the methods of Cason and Corneia (49), and Tipson, Clapp and Cretcher (50), respectively, were unsuccessful and starting tosylate was recovered

unchanged.

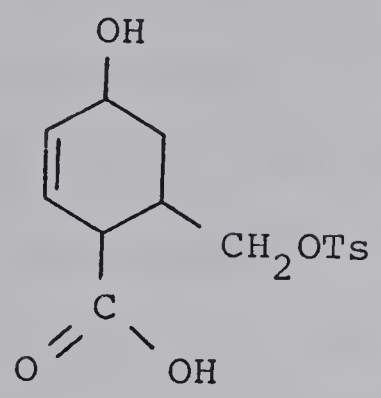
Methanesulphonate (XXII) of XIV

Compound XIV was converted to the mesylate XXII using methanesulphonyl chloride (51). The product was a brown oil which was obtained in 54% yield. The n.m.r. spectrum shows the expected absorption peaks, in the olefinic, bridge-head and methyl proton absorption regions, for the required compound.

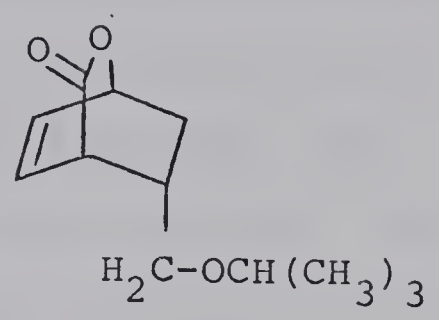
Reaction of XV with Potassium t-Butoxide

In an attempt to convert the tosylate XV to the diene XVI, a solution of XV in t-butyl alcohol (dried over molecular sieves), was treated with a suspension of freshly sublimed potassium t-butoxide in t-butyl alcohol. It was apparent from the colour change of the reaction mixture and slight evolution of heat that a reaction had taken place immediately. Although the colour of the reaction mixture continued to change slowly up to a reaction time of 45 m, aliquots removed from the mixture at 1, 5, 16, and 45 m gave similar n.m.r. spectra upon workup. The product was an almost colourless oil the n.m.r. and i.r. spectra of which are consistent with structure XXIII. The n.m.r. spectrum shows an absorption peak which is exchangeable with D_2O with a relative intensity of two protons. Bridge-head proton absorption peaks

are not visible in this spectrum. The carbonyl absorption



XXIII



XXIV

in the i.r. spectrum is at 1710 cm^{-1} as compared with 1750 cm^{-1} for the lactone.

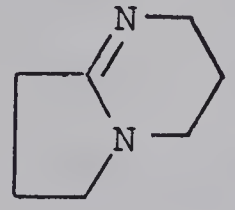
It was difficult to rationalise the formation of XXIII from the above reagents. The starting tosylate, XV, was not sensitive to the workup procedure. It was found, however, that treatment of XV, in t-butyl alcohol, with a dilute aqueous solution of sodium hydroxide gave a product the n.m.r. spectrum of which is similar to that of XXIII, but also contains absorption peaks due to the starting tosylate. The potassium t-butoxide reaction was then repeated using t-butyl alcohol which had been carefully dried (see Experimental section). The n.m.r. spectrum of this product is different from that of XXIII. It cannot be interpreted as that of the required diene, XVI, or of a substitution product (in this case XXIV) as observed by Veeravagn, Arnold and Eigenmann (52) in this type of reaction. No further studies were carried out on this reaction.

Elimination Reactions on XV, XXI and XXII

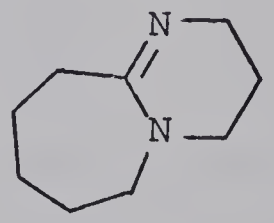
As it was known that these compounds were unstable to heat, and it was thought that the product of elimination, i.e., the diene XVI, would be even less stable, a mild method of elimination was required. The lactone grouping was also known, from previous results, to be attacked by nucleophilic reagents such as hydroxide. Thus, the most suitable bases available for the reaction seemed to be

1,5-diazabicyclo[4.3.0]non-5-ene (DBN) and

1,5-diazabicyclo[5.4.0]undec-5-ene (DBU).



DBN



DBU

Vogel and Klärner (53) were able to prepare 1,2-naphthalene oxide from 5-bromo-4,5-dihydro-1,2-naphthalene oxide using DBN in tetrahydrofuran (THF) at 0°C. DBU was found to be an even better dehydrohalogenation reagent than DBN by Oediger and Möller (54). These two reagents were used (for conditions see Table III) in attempts to prepare XVI. In all cases, except where dioxane was used as the solvent, starting material was recovered unchanged. Where dioxane was used as the solvent the product was not

TABLE III

Conditions of Elimination Experiments

on XV, XXI and XXII

COMPOUND	BASE	SOLVENT	TEMP°C	TIME
XV	DBN	THF	0	30 m
XV	DBN	DMSO	25	overnight
XV	DBN	DMSO	50	2 h
XV	DBN	DMSO	50	20 h
XV†	DBN	THF*	25	2 days
XV†	DBN	THF*	65	67 h
XV	DBU	THF*	65	41 h
XV	DBU	dioxane	80	overnight
XXI	DBU	DMSO	25	30 m
XXII†	DBN	THF*	25	70 h

*Dried and stored over molecular seives.

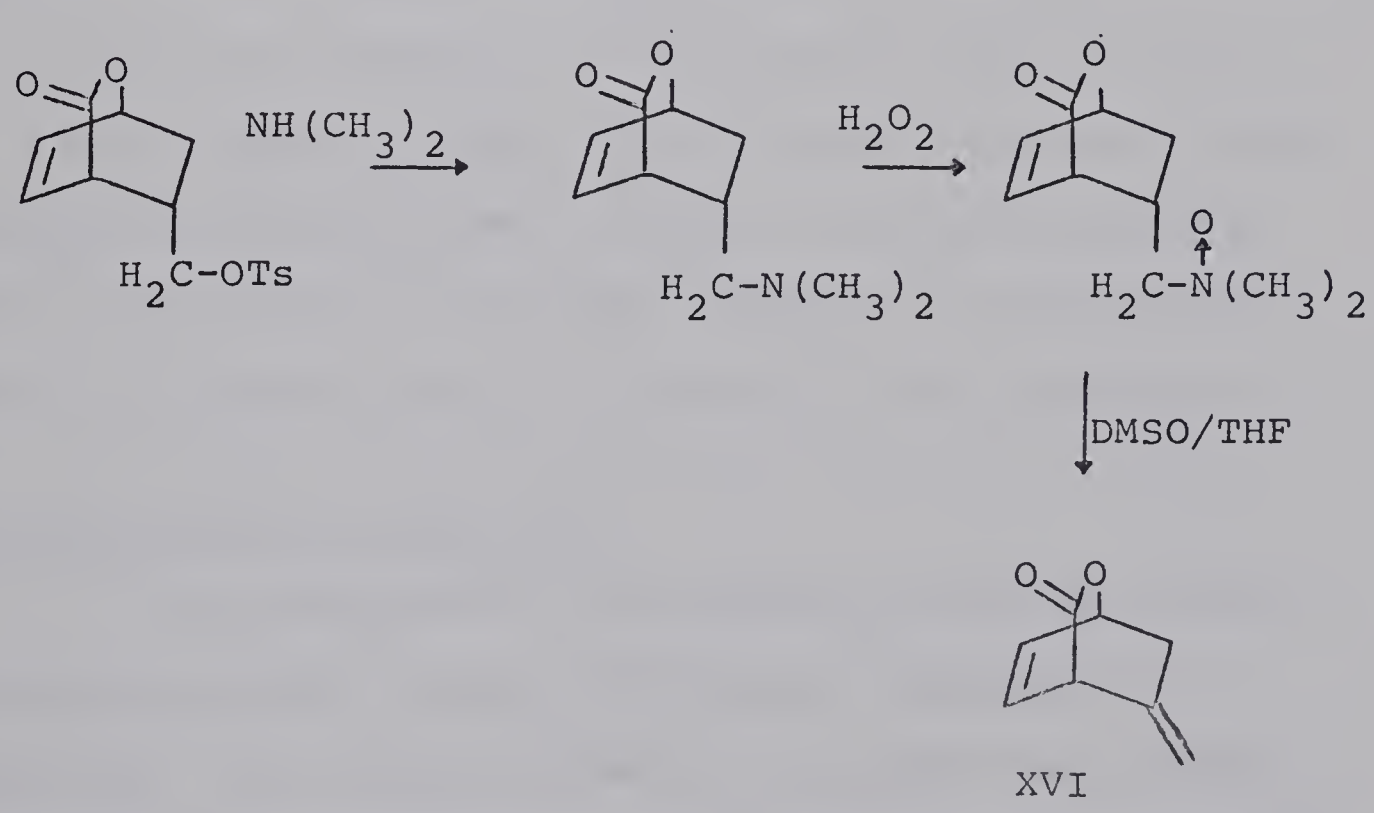
†Reaction carried out under nitrogen.

recognisable from its n.m.r. spectrum.

Reaction of XV with Dimethylamine

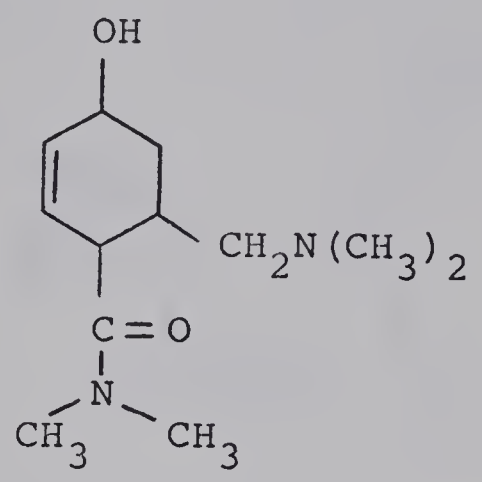
Another method was required for the preparation of XVI as elimination attempts on XV, XXI and XXII were unsuccessful. Cram and Sahyun (55) found that amine oxides could be converted to the corresponding olefins at room temperature by treatment with dry dimethyl sulphoxide (DMSO) or THF. It was thus proposed that Scheme IV be modified in the following manner,

SCHEME IVa



The tosylate XV was treated with dimethylamine according to the method of Cope and Bumgardner (56). Upon workup

however, the reaction gave starting tosylate and a material the n.m.r. and i.r. spectra of which can be rationalised to be due to the following structure,

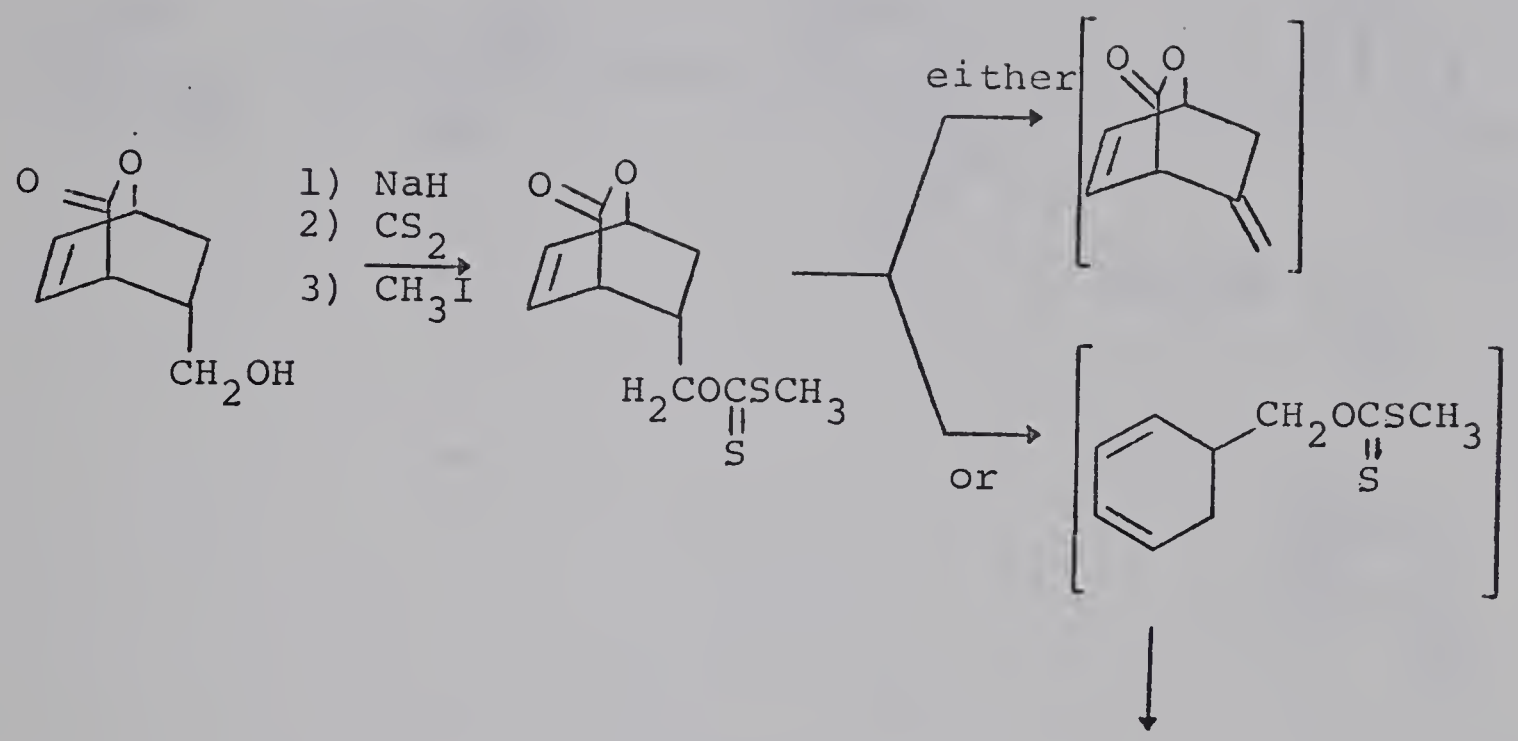


The n.m.r. spectrum shows two singlets (τ 6.95) with a relative intensity of six protons which could be due to the amide methyl groups. It also shows a singlet (τ 7.75) with a relative intensity of six protons which could be due to amine methyl groups. Olefinic and hydroxyl proton absorptions are also shown. The i.r. spectrum shows a carbonyl absorption at 1615 cm^{-1} which is in the amide carbonyl absorption region. Scheme IVa was abandoned.

Other Precursors to Diene XVI

The pyrolysis of the xanthate ester of alcohol XIV should give the triene X directly, according to Scheme IVb. An attempt was made to prepare the xanthate ester of XIV using sodium hydride, carbon disulphide and methyl iodide by the method of O'Connor and Nace (57) but the starting material was recovered unchanged.

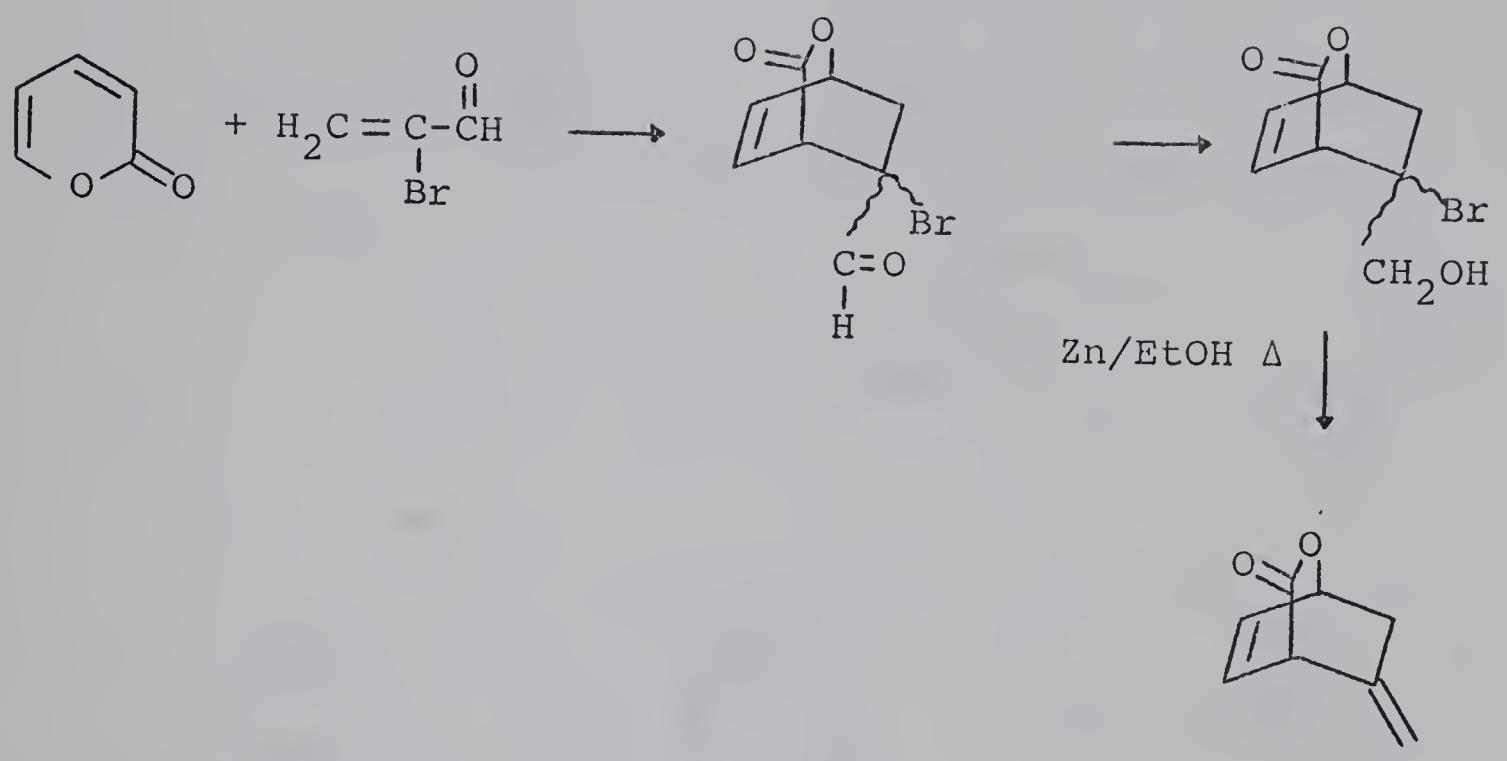
Scheme IVb



X

It has been reported in the literature (58,59) that some bromohydrins are converted to the corresponding olefins by treatment with zinc or a zinc/copper couple under relatively mild conditions, e.g., refluxing ethanol. This suggested that Scheme IV might be further modified to Scheme VI. α-Bromoacrolein was readily prepared by the method of Baker, et al. (60), from acrolein and bromine. This material proved to be very unstable, however. It was found to be considerably discoloured after standing for 2 h over hydroquinone in a refrigerator. An attempt to make the Diels-Alder adduct of α-bromoacrolein

Scheme VI



with α-pyrone yielded only polymeric material.

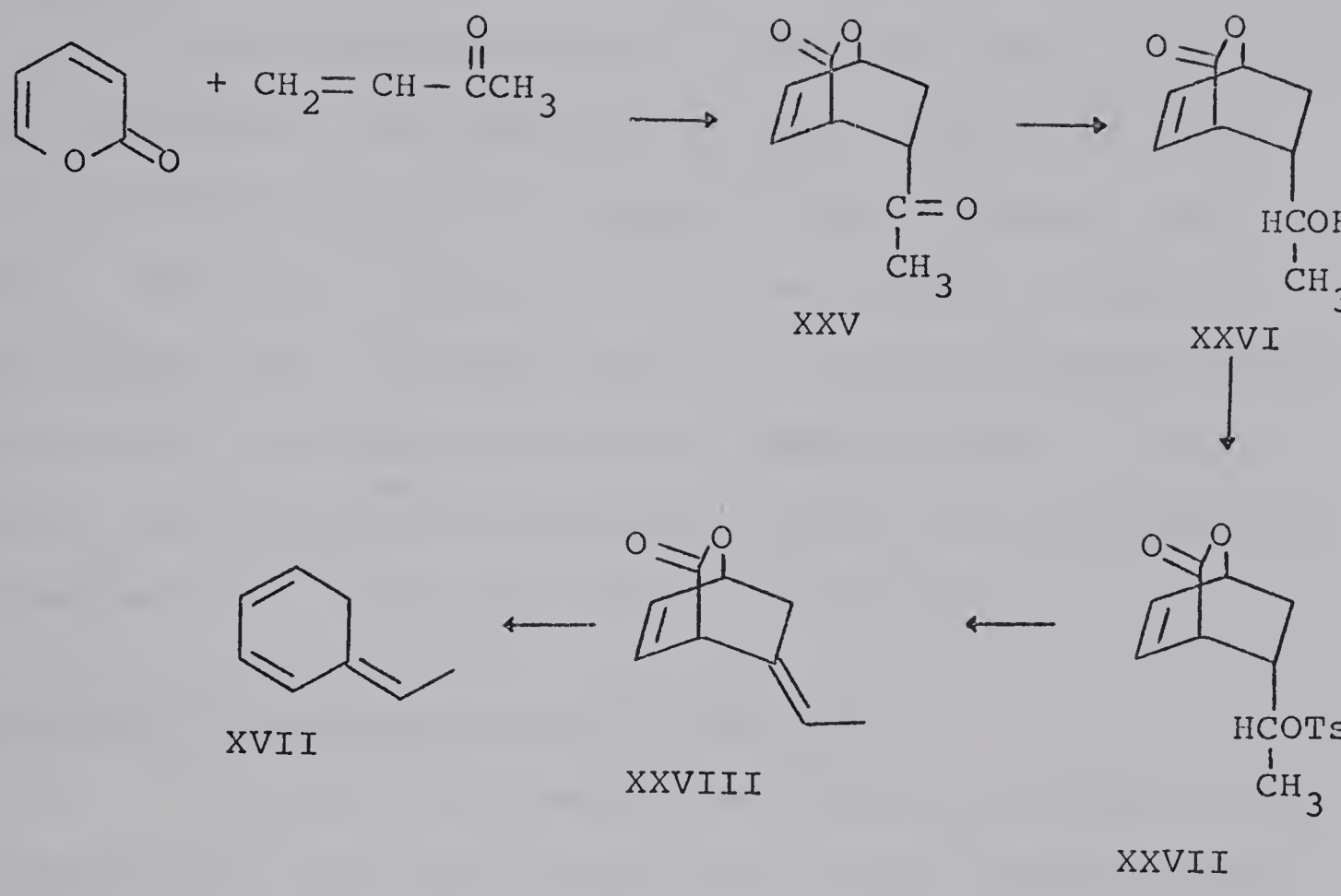
5-Ethylidene-1,3-cyclohexadiene, XVII

As attempts to prepare the diene XVI were unsuccessful a modification of Scheme IV was used to prepare the diene XXVIII and subsequently triene XVII. Methyl vinyl ketone was used as the dienophile for the Diels-Alder reaction shown in Scheme VII. (Stereochemistry shown by analogy to Scheme IV).

Diels-Alder Adduct of α-Pyrone and Methyl Vinyl Ketone--endo-5-Acetyl-2-oxabicyclo[2.2.2]oct-7-en-3-one, XXV

Compound XXV was prepared by the same method as

Scheme VII



was used to prepare XIII, except that a bath temperature of 65°C was used. The yields (calculated in the same way as the yields of XIII) were almost quantitative. A similar difficulty was found in the attempted removal of the unreacted α-pyrone. The n.m.r. spectrum of the product is very similar to that of XIII, except for the expected substitution of a ketonic methyl proton absorption for the aldehydic proton absorption. It is not possible to tell from the spectrum whether there are any minor ketonic methyl proton absorption peaks present which could be due to other isomers of XXV.

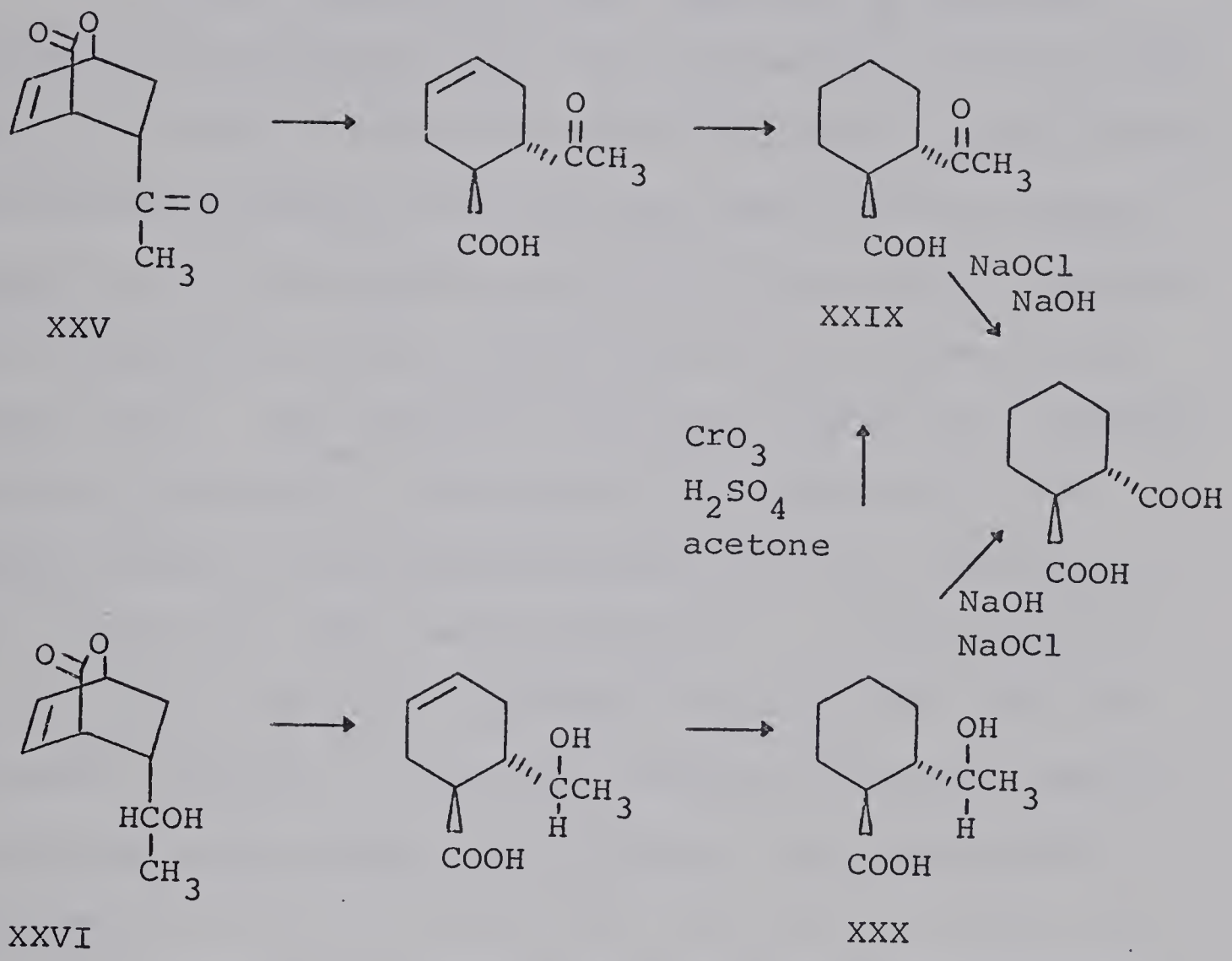
endo-5-(1-Hydroxyethyl)-2-oxabicyclo[2.2.2]oct-7-en-3-one, XXVI

The reduction of XXV to XXVI was carried out in the same way as the reduction of XIII to XIV. No solid precipitated from the oil formed by this reaction, however. The n.m.r. spectrum is not as "clean" as that of the adduct XXV. Although the n.m.r. spectrum shows absorption in the regions expected for compound XXVI, it also shows a few absorption peaks that cannot be accounted for, consequently it does not integrate correctly.

Structure Determination on XXV and XXVI

A similar series of reactions was carried out on compounds XXV and XXVI as was used for the determination of the structure of XIV. The oxidation step in Scheme V was substituted by a haloform reaction in Scheme VIII. Only poor yields of oils were obtained for compounds XXIX and XXX, the n.m.r. spectra of which cannot be properly rationalised as being due to the required compounds.

Scheme VIII



Compounds XXIX and XXX gave positive iodoform tests but no trans-1,2-cyclohexanedicarboxylic acid, or other isomers of cyclohexanedicarboxylic acid, could be obtained from the haloform reactions carried out on these compounds.

For comparative purposes and for use as a model compound for the haloform reaction some authentic trans-2-acetylcyclohexanecarboxylic acid was prepared.

trans-2-Acetylcyclohexanecarboxylic acid

This compound has been reported by Hertzler, Berdahl and Eisenbraun (61), but no spectral or analytical data were given. The method used to prepare trans-2-acetylcyclohexanecarboxylic acid was not that of these authors. trans-1,2-Cyclohexanedicarboxylic acid was first converted to the anhydride using acetyl chloride by the method of Baeyer (62). The anhydride was then treated with dimethyl cadmium according to the method of De Benneville (63). trans-2-Acetylcyclohexanecarboxylic acid was isolated in 55% yield (from the starting diacid) as a white crystalline solid. The n.m.r. spectrum is consistent with the required compound. Elemental analysis repeatedly gave a value for carbon which was 0.5% low, (see Experimental section).

Using an aqueous solution of sodium hypochlorite and sodium hydroxide in a slightly modified form of Newman and Holmes' method (64), trans-2-acetylcyclohexanecarboxylic acid was converted back to trans-1,2-cyclohexanedicarboxylic acid in 65% yield. The diacid was precipitated immediately from the reaction mixture upon workup.

Repetition of the above haloform reaction on either XXIX or XXX gave no precipitate of the diacid and

none could be isolated from the reaction mixtures. Treatment of the oil XXX with Jones reagent (65) gave another oil which did not crystallise to give solid trans-2-acetylcyclohexanecarboxylic acid. The spectral data is inconclusive.

The failure of the sequence of reactions given in Scheme VIII to give any cyclohexanedicarboxylic acid from XXV or XXVI is not understood. The n.m.r. spectra of XIII and XXV are so similar, however, that it is felt that these adducts must both have the same basic structure. As an example, the exo form of XIII would have the proton on C-5 in quite a different environment and this should be readily observable in the n.m.r. spectrum.

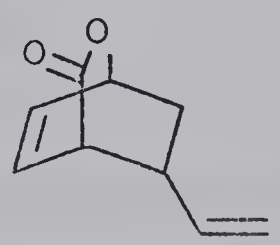
p-Toluenesulphonate (XXVII) of XXVI

The crude alcohol XXVI was used to prepare the tosylate XXVII in a manner similar to that described for the preparation of XV. A brown oil was produced in about 50% yield. It was found, however, that about a 20% yield (from starting alcohol) of a white solid could be obtained by refluxing the oil in diethyl ether. The i.r. and n.m.r. spectra of this solid are similar to those of tosylate XV and are consistant with the proposed structure. The n.m.r. spectrum of the remaining oil is very similar to that of the solid but shows a few absorption peaks which cannot be accounted for. Only the solid tosylate XXVII was used

in the subsequent elimination reactions.

Elimination Reactions on XXVII

The bases used for the elimination reactions on XXVII were DBN, DBU and 1,8-bis-(dimethylamino)-naphthalene. 1,8-Bis-(dimethylamino)-naphthalene is another base of reactivity (66) similar to that of DBN or DBU. It is almost completely non-nucleophilic (67) and was thought to be an ideal reagent for the elimination reaction. The conditions and results of the elimination reactions are presented in Table IV. The elimination product, A, was a yellow oil. The n.m.r. spectrum shows absorption peaks in the regions expected for the diene XXVIII. The spectrum is more complicated, however, than would be expected for XXVIII and shows absorption peaks which could be due to the other possible elimination product XXXI. Although no separation of the elimination product, A, could be



XXXI

achieved by t.l.c., gas-liquid chromatography (g.l.c.) showed that several compounds were present (see Figure I). A peak corresponding to ethylbenzene and a peak corresponding to styrene were observed on the chromatogram.

TABLE IV

Elimination Reactions on XXVII

BASE	SOLVENT	TEMP, °C	TIME	PRODUCT
DBN	THF	64	40 m	XXVII
DBU	DMSO	60	2 days	XXVII + A
DBU	DMSO	85	16 h	XXVII + 32% A
DBU	t-butyl alcohol	80	2 days	XXVII + 43% A
DBU	t-amyl alcohol	105	16 h	Not identified
DBU	t-amyl alcohol	95	17 h	XXVII + 19% A
DBU	t-amyl alcohol	95	2 days	Not identified
DAN*	pyridine	25	2 h	XXVII
DAN	pyridine	75	66 h	XXVII
DAN	DMSO	90	18 h	XXVII
DBU	DMSO	85	19 h	53% A
DBU	DMSO	85	16 h	XXVII + 28% A

*1,8-bis-(dimethylamino)-naphthalene--usually referred to by its trade name, i.e., Proton Sponge.

Product yield was determined by weight after workup as described in the Experimental section. The nature of the product was determined by n.m.r. spectroscopy.

FIGURE I

G.l.c. trace of

a A

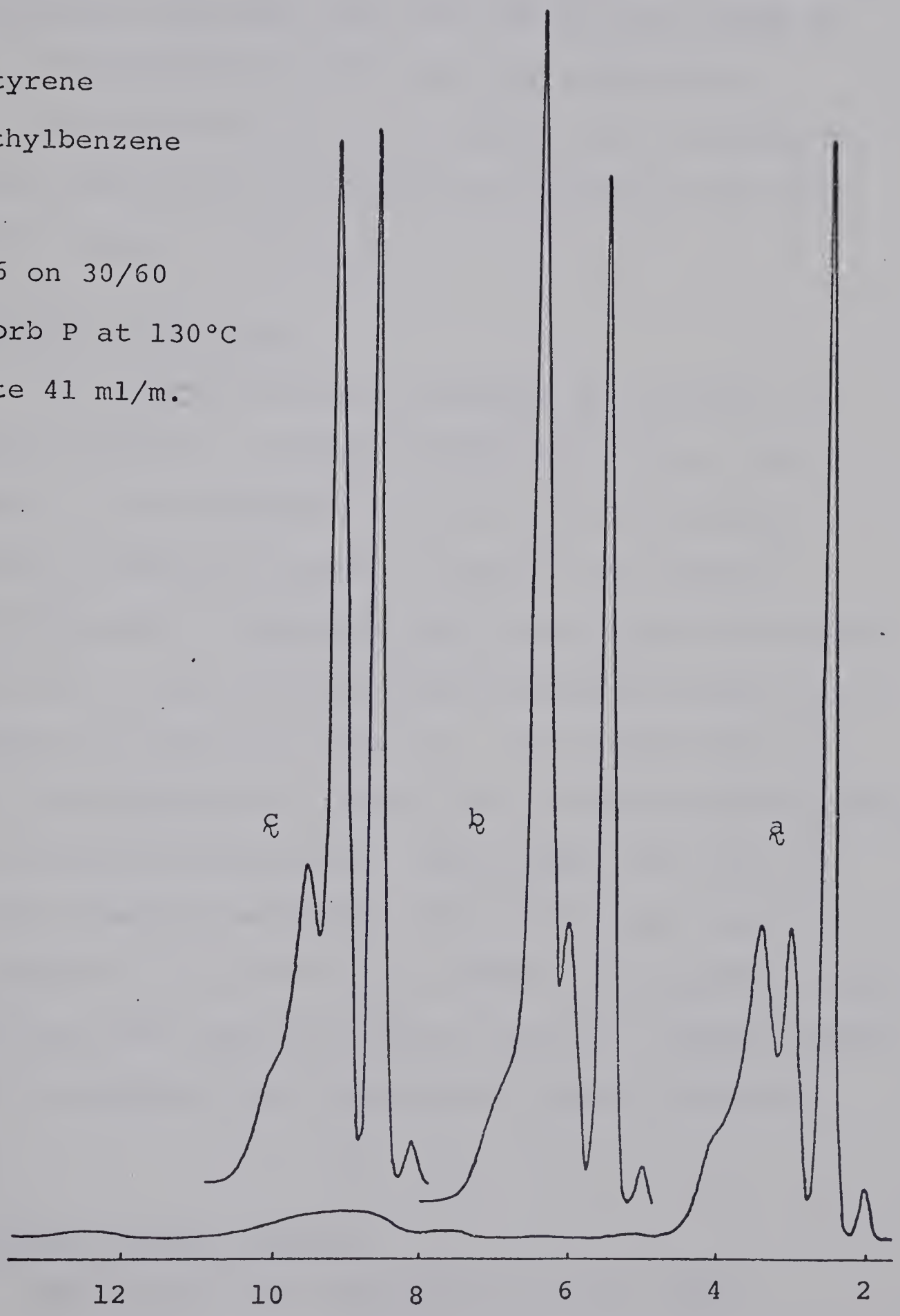
b A + styrene

c A + ethylbenzene

On SF 96 on 30/60

chromosorb P at 130°C

flow rate 41 ml/m.



The identity of the peaks was checked by mixed injections with authentic compounds using the conditions listed in Table V. The remaining peaks were not identified.

Ethylbenzene was also detected in the reaction mixture of the elimination reaction of XXVIII using DBU in t-amyl alcohol at 95°C.

Polymerisation of Styrene

The polymerisation of styrene was carried out in sealed ampoules. A pilot run was carried out using one sample of pure styrene, and one sample of styrene with some A (initiator) added. A second run had the initiated samples in duplicate and the uninitiated samples in triplicate. The conditions and results of these polymerisations are given in Table VI. The polymer was isolated by precipitation by ethanol then reprecipitation from benzene solution by methanol. The polymer was then filtered off, dried and weighed. The polymer from the initiated samples of the second run seemed to be somewhat less viscous than that from the control samples. Suitable apparatus for confirming this observation was not available, however.

Decomposition Product of XIV

The alcohol XIV was heated to 140°C under reduced pressure and the product of decomposition XXXII

TABLE V

G.l.c. Conditions for Mixed Injections

COLUMN	COLUMN TEMP, °C	FLOW RATE ML/M	INJECTOR TEMP, °C	RETENTION TIME (M) ETHYL-BENZENE	STYRENE
20% SF 96	130	41	300	3.10	3.45
on 30/60	100	40	296	7.45	8.90
chromosorb P	130	56	300	2.25	2.55
10% Carbowax 400 on Du Pont 60/80	75	77	290	5.05	6.10

TABLE VI

Polymerisation of Styrene

	WT., (g) STYRENE	WT. A (mg)	WT., (mg) POLYMER	% POLYMER-ISATION	R_p mole l^{-1} s^{-1} x10^5
RUN 1	5.365	77	75	1.40	3.13
80°C	4.601	--	41	1.12	2.51
2 h					
RUN 2	5.084	79	264	5.20	11.63
97.5°C	4.912	74	253	5.15	11.54
1 h	5.194	--	94	1.81	4.05
	4.085	--	70	1.71	3.83
	4.046	--	60	1.48	3.32

Average R_p for initiated samples = 11.59 x10^{-5} mole l^{-1} s^{-1}

Average R_p for uninitiated samples = 3.73 x10^{-5} mole l^{-1} s^{-1}

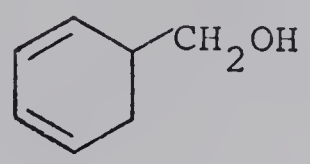
Therefore R_{pi} = 7.86 x10^{-5} mole l^{-1} s^{-1}

Estimated k_d at 100°C = 9.7 - 15.0 x10^{-6} s^{-1}

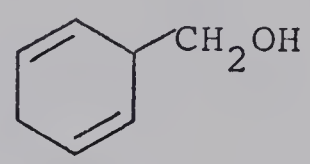
Average [I] = 1.70 - 5.11 x10^{-2} mole l^{-1}

Kinetic chain length ν = 100 - 480

collected in a trap cooled by a Dry Ice-acetone bath. The n.m.r. spectrum of the product shows absorption peaks in



XXXII



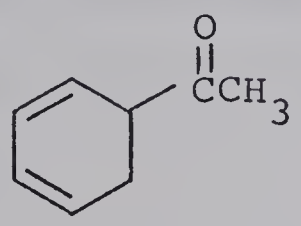
XXXIII

the olefinic and allylic proton absorption regions which could be due to the expected product of decarboxylation of XIV, namely 1-hydroxymethyl-2,4-cyclohexadiene, XXXII, or the unconjugated isomer of XXXII, 1-hydroxymethyl-2,5-cyclohexadiene, XXXIII. The u.v. spectrum, however, shows an absorption peak (λ_{max} 259 log ε 3.67) in the absorption region of conjugated cyclic dienes. It is thus assumed that XXXII is the product. Further confirmation was provided by the treatment of XXXII with tetracyanoethylene (TCNE) using the method of Middleton, et al. (68), which gave the expected Diels-Alder adduct.

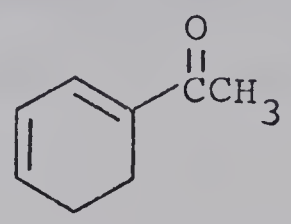
Decomposition Product of XXV

Compound XXV could not be obtained free of α-pyrone even after prolonged heating of the impure XXV at 100°C under reduced pressure. Heating XXV at 140°C under reduced pressure gave the expected decarboxylation product XXXIV, methyl 2,4-cyclohexadien-1-yl ketone, contam-

inated with a small percentage of α-pyrone. It was found that the α-pyrone could be separated from the mixture by



XXXIV



XXXV

column chromatography, using silica gel and eluting with 2:5, diethyl ether: Skelly B. However, during the course of the chromatography some XXXIV was dehydrogenated to acetophenone (69) as can clearly be seen from the n.m.r. spectrum of the product. The n.m.r. and u.v. spectra of the product clearly indicate that XXXIV, and not the diene conjugated with the carbonyl group, i.e. XXXV or the unconjugated diene, is the product. The n.m.r. spectrum shows absorption in the olefinic proton absorption region (τ 4.15) corresponding to four protons. The n.m.r. spectrum of XXXV would only show an absorption corresponding to three protons in this region. The u.v. spectrum shows an absorption peak at λ_{max} 264 mμ (log ε 3.12). Compound XXXV would be expected to absorb at λ_{max} ∿300 mμ. A Diels-Alder adduct of XXXIV was made using TCNE (63).

Kinetics of Decomposition of XIV and A

A small sample of the compound under study was

dissolved in ethyl benzoate, heated and the carbon dioxide evolved measured at given intervals of time.

Retro Diels-Alder decarboxylations are unimolecular (70). The rate constant is given by the first-order rate expression,

[16] $$k_d = \frac{1}{t} \ln \frac{(V_\infty - V_o)}{(V_\infty - V_t)}$$

where t = time

V_∞= volume of gas evolved at infinite time

V_t= volume of gas evolved at time t

The half-life of the reaction can be obtained from the rate constant by using the following relationship,

$$t_{1/2} = \frac{\ln 2}{k_d}$$

A graphical plot of $(V_\infty - V_t)$ versus t gives a line of slope $-k_d/2.303$. The term $(V_\infty - V_o)$ only affects the intercept of the graph and not the slope from which the rate constant is determined. This expression was used for the decomposition of XIV at 150°C, where 95% of the theoretical volume of carbon dioxide was evolved, and for the decarboxylation of A at 140°C.

Although a plot of $(V_\infty - V_t)$ v.s. t gives a straight line over about 3 half-lives for the decarboxy-

lation of XIV at 130°C, only 68% of the theoretical amount of carbon dioxide was evolved. Consequently another rate expression was used,

[17] $$-k = \frac{1}{t} \ln \frac{(V_T - FV_t)}{V_T}$$

where k = rate constant for disappearance of XIV

V_T= theoretical value of V_∞ (if all of XIV decarboxylates)

$$F = k/k_1 = 1 + \left(\left(1-\frac{V_\infty}{V_T}\right)\Big/\frac{V_\infty}{V_T}\right)$$

k_1= rate constant for decarboxylation of XIV

For the derivation of this expression see Appendix.

A plot of log $(V_T - FV_t)$ versus t gives a line of slope $-k/2.303$. The term $/V_T$ is a constant and does not affect the slope of the line.

As only approximate data was required no duplicate runs were carried out. The rate data is given in Tables VII, VIII and IX and the corresponding graphical plots are shown in Figures II, III and IV.

TABLE VII

Rate Data for the Decarboxylation of XIV at 130°C

Wt. of sample = 196 mg

TIME (m)	BURETTE READING (ml)	$(V_T - FV_t)$	log $(V_T - FV_t)$
0	40.8	34.2	
2	39.9	32.9	1.52
4	39.7	32.7	1.51
12	39.0	31.6	1.50
22	38.0	30.1	1.48
32	37.2	29.1	1.46
42	36.5	27.9	1.44
58	35.0	25.7	1.41
72	33.9	24.1	1.38
82	33.1	22.9	1.36
102	31.9	21.1	1.32
128	30.5	19.1	1.28
159	28.7	16.4	1.21
197	27.0	13.9	1.14
238	25.2	11.3	1.05
307	23.3	8.5	0.93
358	22.0	6.4	0.81
419	21.2	5.4	0.73
1783 (∞)	17.2		

V_∞ = 23.6 ml V_T = 34.2 ml $F = 1 + \frac{8}{17} = 1.47$

$k = 7.45 \times 10^{-5}\ s^{-1}$ $\quad t_{1/2} = 154$ m

$k_1 = 5.07 \times 10^{-5}\ s^{-1}$ $\quad t_{1\ 1/2} = 227$ m

FIGURE II

Plot of log $(V_T - FV_t)$ vs time for gas evolution in the decarboxylation of XIV at 130°C

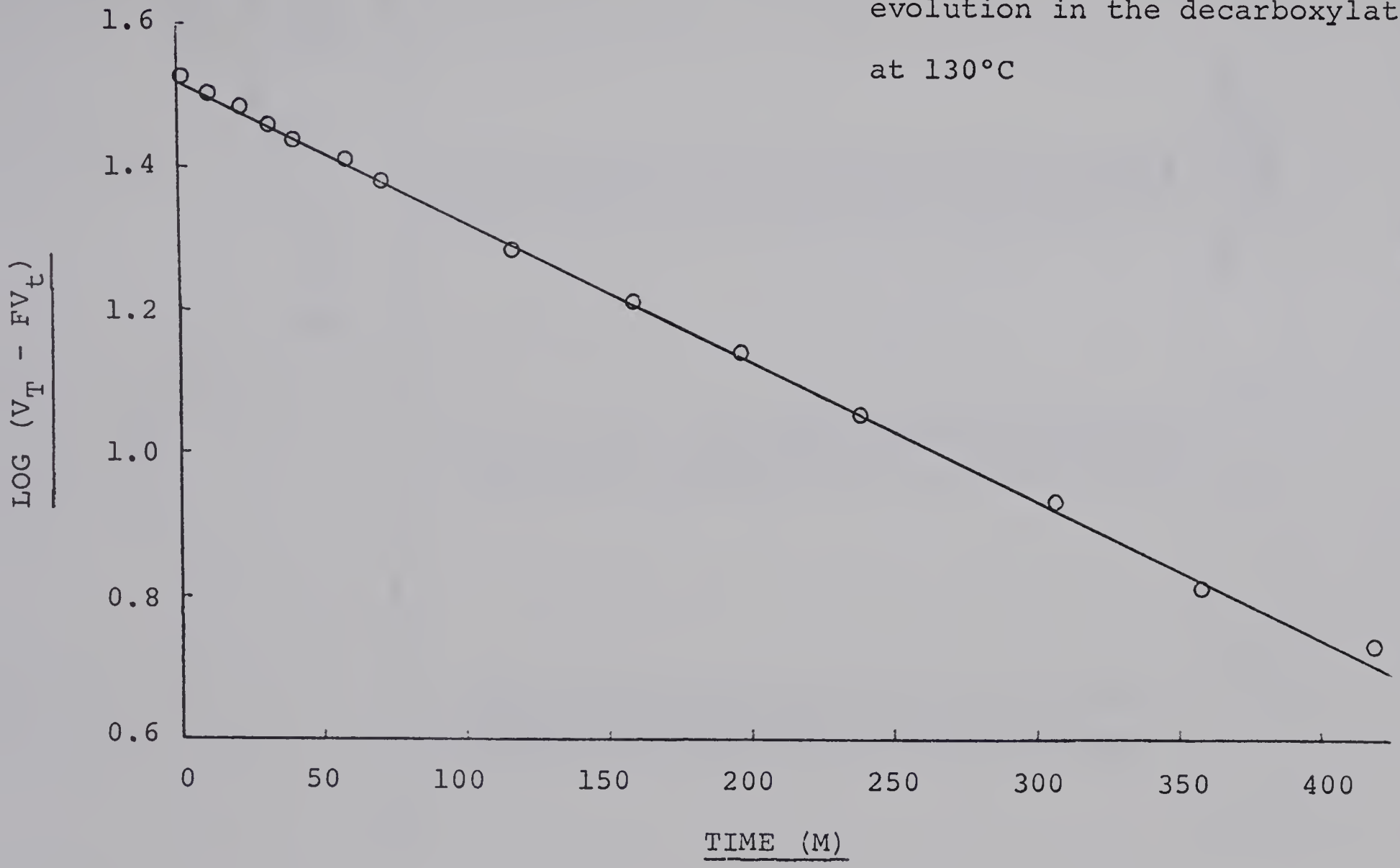


TABLE VIII

Rate Data for the Decarboxylation of XIV at 150°C

Wt. of sample = 160 mg

TIME (m)	BURETTE READING (ml)	$(V_\infty - V_t)$	log $(V_\infty - V_t)$
0	43.1	26.6	
2	42.1	25.6	1.41
5	41.2	24.7	1.39
8.5	40.2	23.7	1.38
13.5	38.9	22.4	1.35
16	37.7	21.2	1.33
21	35.8	19.3	1.29
26.5	34.1	17.6	1.25
32.5	32.5	16.0	1.20
39	31.0	14.5	1.16
42	30.8	14.3	1.15
53	28.5	12.0	1.08
58	27.6	11.1	1.05
67	26.2	9.7	0.99
75	25.3	8.8	0.95
79	24.9	8.4	0.92
90	23.9	7.4	0.87
100	23.2	6.7	0.83
111	22.7	6.2	0.79
120	22.3	5.8	0.76
130	22.0	5.5	0.74
142	21.7	5.2	0.72
163	21.3	4.9	0.69
303	20.5	4.0	0.60
∞	16.5	--	--

V_∞ = 26.6 ml V_T = 28.1 ml

$k_d = 2.48 \times 10^{-4}\ s^{-1}$

$t_{1/2}$ = 46 m

FIGURE III

Plot of log $(V_\infty - V_t)$ vs time for gas evolution in the decarboxylation of XIV at 150°C

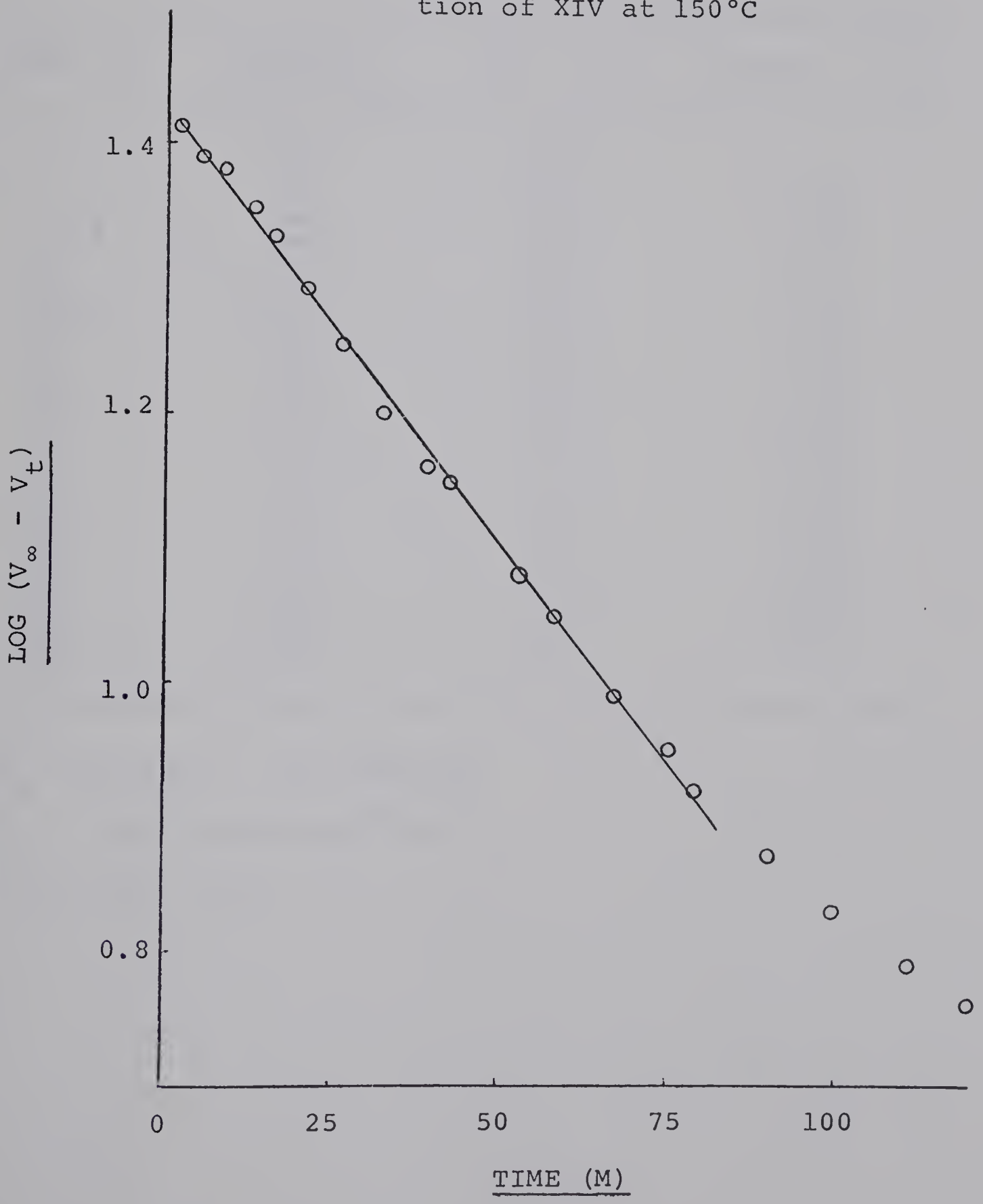


TABLE IX

Rate Data for the Decarboxylation of A at 140°C

Wt of sample = 218 mg

TIME (m)	BURETTE READING (ml)	$(V_\infty - V_t)$	log $(V_\infty - V_t)$
0	45.4	22.3	
2	44.7	21.6	1.34
4	44.1	21.0	1.32
8.5	43.0	19.9	1.30
14	41.5	18.4	1.27
20	40.0	16.9	1.23
28.5	37.9	14.6	1.16
37	36.3	13.2	1.12
51	34.5	11.4	1.06
58	33.5	10.4	1.02
79	31.7	8.6	0.94
110	30.3	7.2	0.86
134	29.0	5.9	0.77
168	27.6	4.5	0.65
191	27.0	3.9	0.59
247	25.5	2.4	0.38
293	24.9	1.8	0.26
324	24.2	1.1	0.04
506 (∞)	23.1	--	--

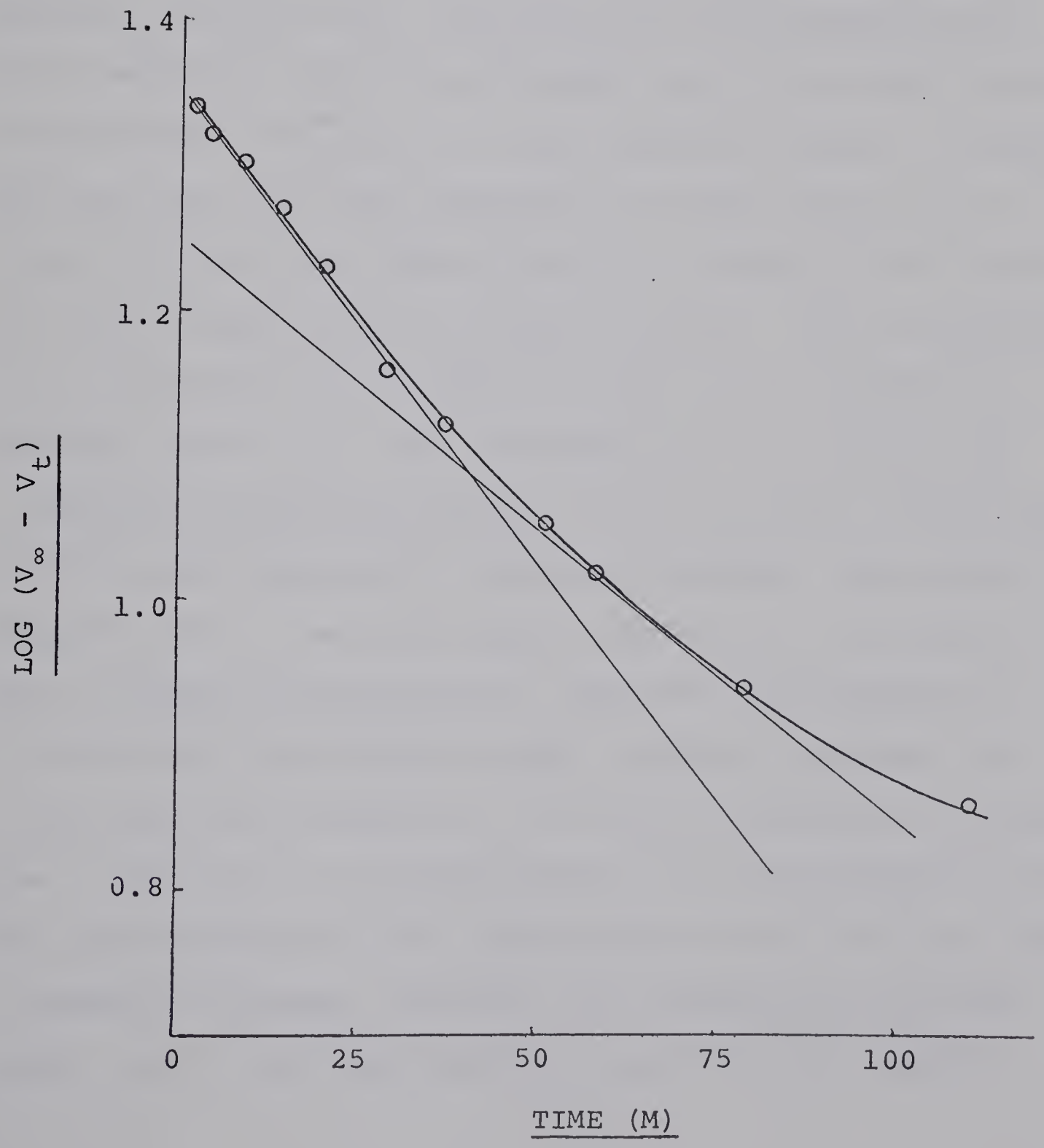
V_∞ = 22.3 ml V_T = 38.8 ml

$k_d = 1.56 - 2.50 \times 10^{-4}\ s^{-1}$

$t_{1/2}$ = 46 - 74 m

FIGURE IV

Plot of log $(V_\infty - V_t)$ vs time for gas evolution from the decarboxylation of the elimination product of XXIII at 140°C



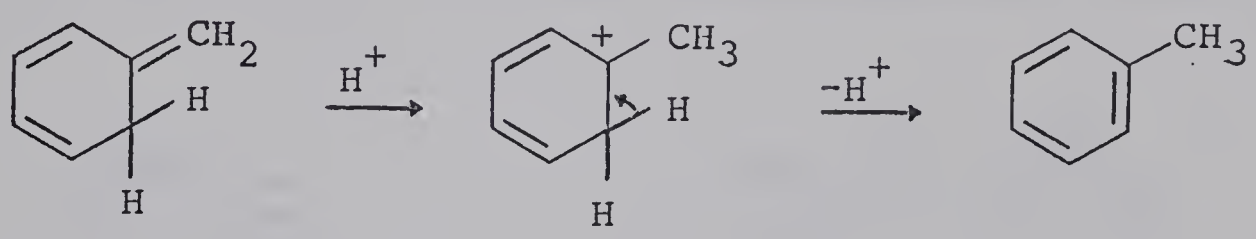
DISCUSSION

Approach to the Syntheses of 5-Methylene-1,3-cyclohexadiene and 5-Ethylidene-1,3-cyclohexadiene

5-Methylene- and 5-ethylidene-cyclohexadiene, X and XVII, are tautomers of toluene and ethylbenzene, respectively. Horning (71) has suggested that such compounds would be unavailable due to the much higher thermodynamic stability of their aromatic isomers. Bailey and Baylouny (30) have prepared X in small quantities in a pure form and have found that it is stable at -78°C and at higher temperatures in dilute solution. This compound, X, is predicted to be thermally stable by the Woodward-Hoffmann Rules (72). The conversion of X to toluene by a concerted mechanism requires a [1,3] or [1,7] (which are in this case equivalent), symmetry-forbidden, suprafacial hydride shift. The same argument applies to the conversion of XVII to ethylbenzene. This does not preclude X or XVII from isomerising to their aromatic tautomers via a non-concerted mechanism. It is also interesting to note that 3-methylene-1,4-cyclohexadiene has been prepared (73). The isomerisation of this compound to toluene could go via a thermally allowed, concerted [1,5] suprafacial hydride shift. Both X and XVII would be expected to be rapidly

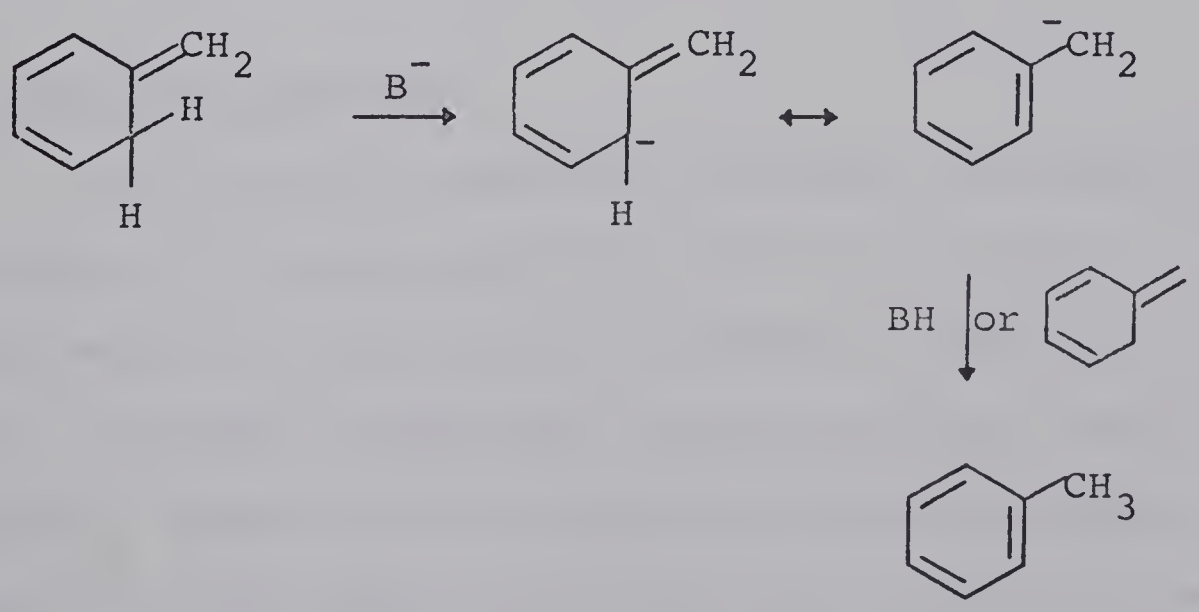
isomerised to their aromatic isomers in the presence of acidic or basic catalysts. Addition of a proton to the methylene carbon of X would give a stable tertiary-allylic carbonium ion which could then lose a proton to give toluene, eq [18].

[18]

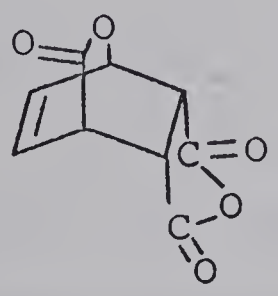


The hydrogens on C-6 of X are doubly allylic (with the qualification that ring strain may cause imperfect over-lap of the developing occupied p-orbital with the existing olefinic p-orbitals) and thus readily abstracted by base. The resulting anion could then abstract a proton from another molecule of X or from the protonated base, eq [19].

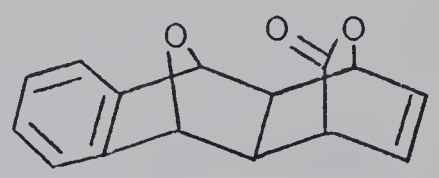
[19]



In the light of the foregoing a synthetic scheme was sought in which X could be prepared under mild conditions in a neutral environment. Goldstein and Thayer (70) and Fieser and Haddadin (74) found that compounds XXXVI and XXXVII, repsectively, could be decarboxylated at relatively low temperatures to give the corresponding dienes.



XXXVI



XXXVII

This suggested that XVI might be a useful precursor to X as acid or base is unnecessary for the conversion. Scheme IV thus seemed to be suitable for the preparation of XVI and subsequently X, as the reaction types employed in it have been well documented.

The Diels-Alder Reaction

The reaction conditions used for the addition of acrolein to α-pyrone were dictated by practical considerations and the stability of the adduct. Acrolein boils at 52°C. A higher temperature could have been used by utilising a closed system at greater than atmospheric pressure. As the reaction proceded at a reasonable rate,

and the adduct was found to decompose at less than 100°C, the conditions as stated in the Experimental section were used. The production of polymer in the attempted catalysis of the Diels-Alder reaction was probably due to the sensitivity of the α-pyrone to the catalysts. Acrolein has been used with these catalysts and other dienes by other workers (35,36).

Reduction Reaction

Molecular models indicate that the lactone system of the adduct XIII and its derivatives is rather strained. This probably accounts for the sensitivity of XIII and/or XIV towards the reduction reaction conditions.

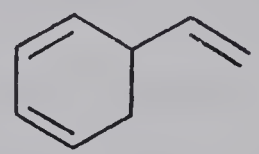
Elimination Reactions

There are several problems associated with the conversion of XV to the diene XVI. The preservation of the lactone grouping is of importance as it is unlikely that it could be reformed, if it were opened, due to the strain in the system. It was suspected, and subsequently confirmed (see Results), that the lactone grouping would be sensitive to nucleophilic attack. This required that a non-nucleophilic base or base of low nucleophilicity be used for elimination. The literature provides numerous examples of bases which fit this requirement, but the conditions under which they are used require temperatures

which are too high to be used with this system. Decarboxylation of A takes place at an appreciable rate at about 100°C. Masamune (75) suggested that DBN or DBU might be useful bases as they have been used at temperatures in the region of -15°C. There are also examples in the literature (53) of these bases being used for low temperature elimination reactions.

Tosylate XV, in fact, proved to be unreactive towards these bases under mild conditions. Secondary tosylates are known to be, in general, more reactive towards elimination than primary tosylates. Thus Scheme VII was devised to give the secondary tosylate XXVII. It was hoped that XXVII could be converted to XXVIII and subsequently XVII. Another problem arises with use of XXVII, however. There is now the possibility of elimination taking place to give the undesired compound XXXI, with an external double bond. According to the Saytzeff Rule, (76) which normally applies to tosylates, a predominance of the internal double bond should be formed on elimination. Molecular models show, however, that the hydrogen on C-5 of XXVII is somewhat sterically hindered. Taking into account statistical considerations also, it might be expected that a considerable proportion of XXXI would be formed. This appears to be the case from the results obtained.

The g.l.c. trace of the elimination product, A, shows the presence of ethylbenzene and styrene. The ethylbenzene could arise from decarboxylation of XXVIII in the injection port and subsequent rearrangement of the resulting XVII. This seems to indicate that the required XXVIII is, in fact, formed in the elimination reaction of XXVII. The origin of the styrene is less obvious. Decarboxylation of XXXI would give 5-vinyl-1,3-cyclohexadiene XXXVIII. Dehydrogenation of this compound would give styrene. Dehydrogenation of ethylbenzene would be another



XXXVIII

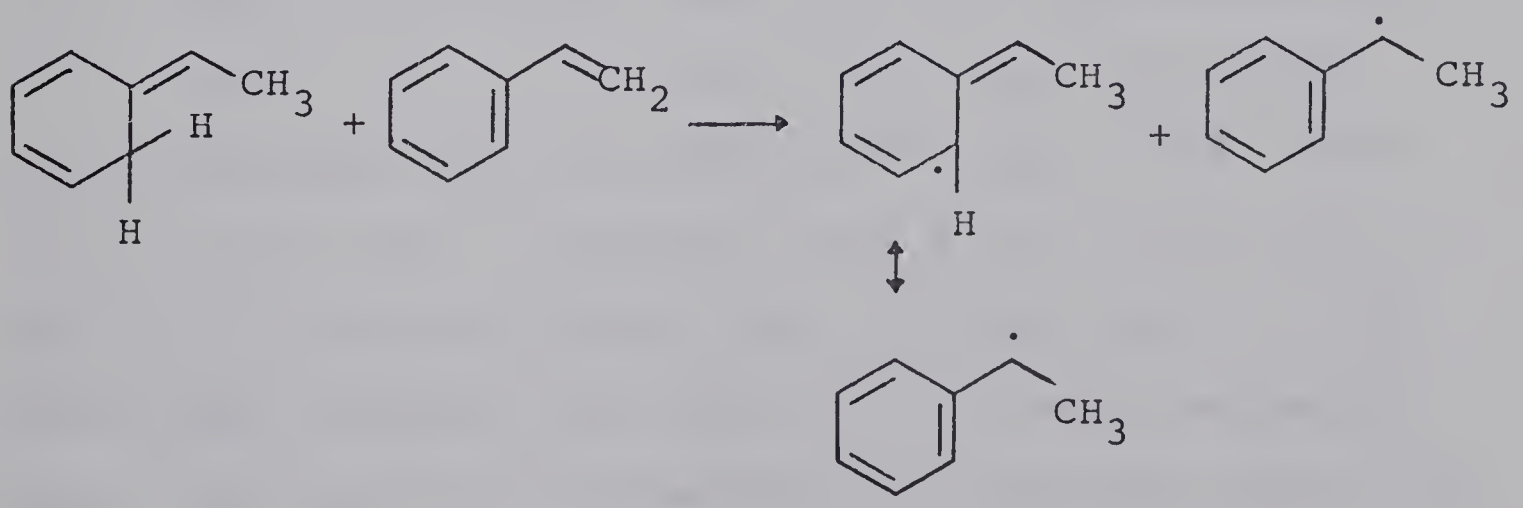
route to styrene. Injection of authentic ethylbenzene under identical g.l.c. conditions did not give rise to a peak corresponding to styrene, however, so this route can be ruled out.

Polymerisation of Styrene

The elimination product, A, was decarboxylated *in situe* with monomeric styrene so that if any of the triene XVII was formed it could react immediately with the styrene. Lack of initiation by A would mean that

either XVII was not formed or that it has no action as an initiator in the polymerisation of styrene. The pilot run at 80°C, seemed to indicate that some initiation was taking place but the result was inconclusive, especially as no duplicate samples were used. The polymerisation at 100°C, however, showed a definite increase in the amount of polymer formed in the samples with A added over that formed from the pure monomer. This result does not require that 5-ethylidene-1,3-cyclohexadiene is the initiating species. 5-Vinyl-1,3-cyclohexadiene could lose a hydrogen from the C-1 or C-6 positions. However, an aromatic canonical form such as XXXIX is not available to the radical so formed, as it is for the radical formed by the loss of a hydrogen at C-6 in XVII. Initiation by XVII could possibly take place as indicated in eq [20].

[20]



XXXIX

The kinetic chain length for the polymerisation of styrene initiated by XVII, produced *in situe*, is given by,

$$[21] \qquad \nu = R_{Pi}/k_d[I]$$

where ν = kinetic chain length

R_{Pi} = rate of polymerisation due to initiation

k_d = rate constant for decomposition of XXVIII

[I] = concentration of XXVIII in styrene

R_{Pi} can be found from the average weight of polymer formed in the initiated samples less the average weight of polymer formed in the control samples. A very approximate estimate of the upper and lower limits of k_d can be obtained by extrapolation of data obtained from Figure IV. Also a very approximate estimate of the upper and lower limits of [I] may be obtained from inspection of Figure I. If the peak at retention time 2.55 m is considered to be due to XXVIII in A (as is the ethylbenzene peak) this gives the upper limit of XXVIII in A, *i.e.*, ∿60%. However, if the peak at retention time 2.55 m is not due to XXVIII in A then the lower limit of XXVIII in A is ∿20%. From these estimates the limits of [I] can be estimated. (*N.B.* the nature of the compound with retention time 2.55 m is not known.) The estimated upper and lower limits for

the kinetic chain length are given in Table VI. The upper limit of ν is found by combining the lower limits of k_d and [I] in eq [21] and the lower limit of ν is found by combining the upper limits of k_d and [I] in eq [21]. The upper limit of ν (480) is of the same order as that calculated for the initiator 2,2'-azobis-(2-methyl-propionitrile), ABN, i.e., 674 (17), at 70°C.

The apparent decrease in viscosity of the polymer from the initiated samples indicates that chain transfer, and subsequent lowering of molecular weight, has taken place, Scheme IX. It is difficult to rationalise XVII as being a more efficient chain transfer reagent than II. The increase in chain transfer in the initiated polymerisations could be due to a higher concentration of XVII, in the reaction mixture, than there is of II in the thermal polymerisation of styrene*. 5-Vinyl-1,3-cyclohexadiene XXXVIII may be acting as a chain transfer reagent, however.

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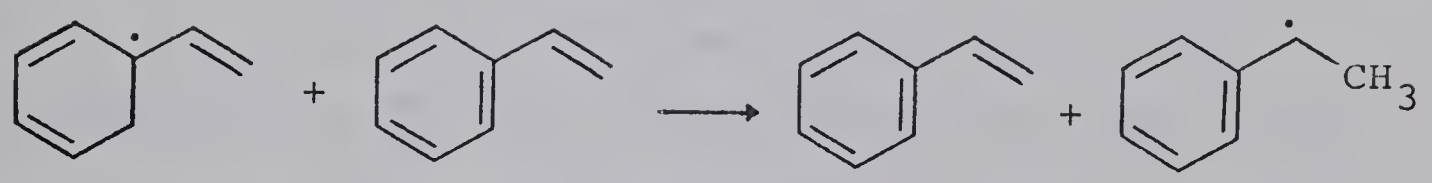
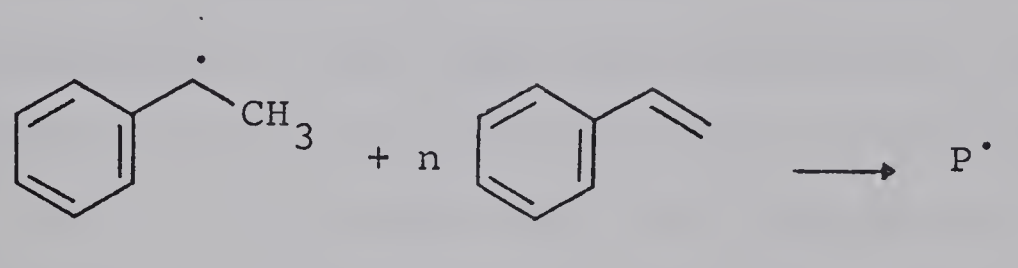
*This argument presupposes that II is, in fact, the initiating species in the thermal polymerisation of styrene.

SCHEME IX

XXXVIII

P· = growing polymer chain





Decarboxylation of the Lactone System

Decarboxylation of the lactone system was first carried out under conditions by which the product of decarboxylation could be isolated. For convenience, compounds XIV and XXV were used as representatives of the lactone system for the two synthetic schemes (i.e., IV and VII). Both gave the expected dienes XXXII and XXXIV in good yield. The structures of XXXII and XXXIV are confirmed by their n.m.r. and u.v. spectra and by the formation of Diels-Alder adducts with TCNE. The n.m.r. spectra of the

adducts show absorption peaks in the olefinic proton absorption region corresponding to two protons. The n.m.r. spectra of compounds XXXII and XXXIV show absorption in the region corresponding to four protons, as would the n.m.r. spectra of possible "ene" addition products of XXXII and XXXIV with TCNE.

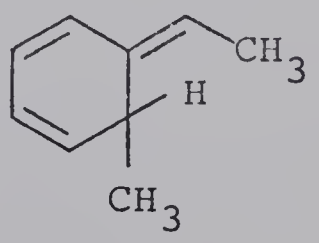
In order to obtain some approximate kinetic data on the decarboxylation of these lactone systems the decomposition of XIV and A were carried out under conditions by which the rate of evolution of carbon dioxide could be measured. This data was required as a guide to the conditions to be used for the study of such species as X and XVII as initiators for the polymerisation of styrene, bearing in mind that X and XVII were to be prepared in situe from XVI and XXVIII, respectively.

At 150°C XIV gave 95% of the theoretical yield of carbon dioxide. It was thus assumed that decarboxylation was the major reaction taking place. A plot of the appropriate first-order rate data gave a straight line over about two half-lives. At 130°C, however, only 68% of the theoretical yield of carbon dioxide was given off. It was thus assumed that some other first-order reaction, that did not give carbon dioxide, was taking place at the same time. A modified rate expression was used and a plot of the appropriate parallel first-order data gave a

straight line over almost three half-lives. This seems to indicate that the assumption is correct. A plot of the first order rate data for the decarboxylation of A at 140°C gives a curve. This is the expected result if it is assumed that two (or more) simultaneous first-order reactions are taking place, both of which evolve carbon dioxide. This would be the case if A contains XXVIII and XXXI. Only 57% of the theoretical amount of carbon dioxide was evolved, however. Thus some other reaction(s) must also be taking place. These could affect the shape of the curve. The rate constants and half-lives calculated from lines shown in Figure IV are intended only for use as a rough guide to the rate of decarboxylation of dienes such as XVI and XXVIII.

Suggestions for Further Investigation

Another compound that could be synthesised from α-pyrone and methyl crotyl ketone by a similar route to those given in Schemes IV and VI is 6-methyl-5-ethylidene-1,3-cyclohexadiene, XXXX.

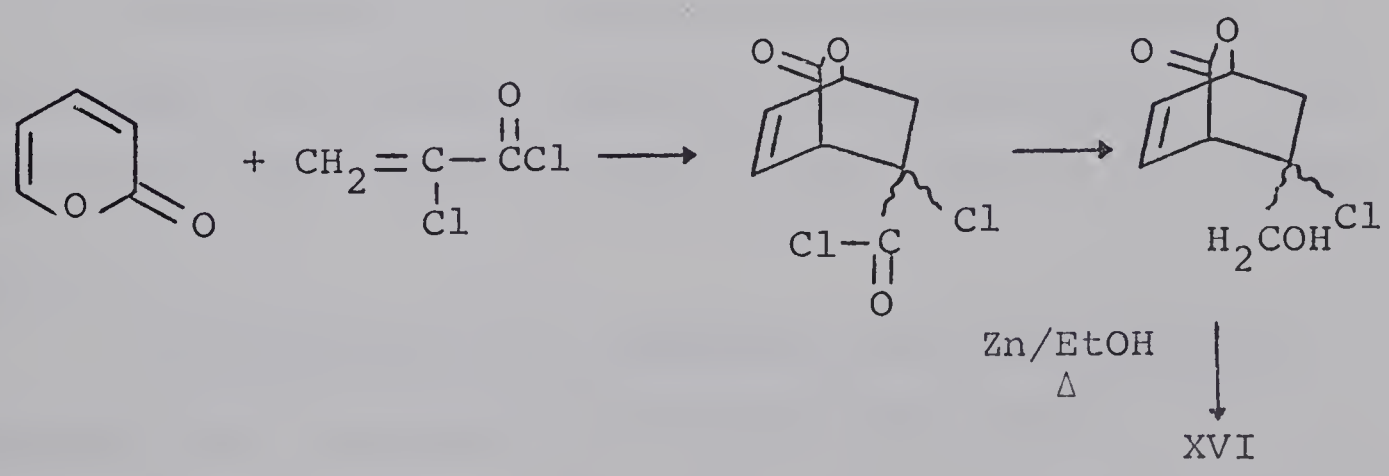


XXXX

This has even closer structural similarities to II than XVII. The same problem of the formation of the external double bond, in the elimination step, would probably arise, however, along with the associated problem of separating the two isomers. This problem would be overcome if a halohydrin elimination were used.

The methylene compound X may be obtainable if a more reactive leaving group than tosylate were used (77). Also the appropriate halohydrin might be prepared by the reduction of the Diels-Alder adduct made from the addition of 2-chloro-acrylylchloride (78) to α-pyrone, Scheme X.

SCHEME X



EXPERIMENTAL

Physical Measurements

All melting points and boiling points are uncorrected. Melting points were taken on either a Gallenkamp heated block melting point apparatus or a Reichert hot-stage microscope.

Nuclear magnetic resonance (n.m.r.) spectra were recorded on Varian Analytical Spectrometers, Models A60 and HR-100, using tetramethylsilane (TMS) as an internal reference. The τ values are reported as relative to TMS = τ 10.0. Abreviations used are s = singlet, d = doublet, t = triplet, q = quartet, and m = multiplet. When one set of absorption peaks is superimposed upon another the abreviation sup. is used.

Infrared (i.r.) spectra were recorded on a Perkin Elmer 337 Grating Infrared Spectrophotometer. The samples were used neat as a thin liquid film or as a solution.

Ultraviolet (u.v.) spectra were recorded on a Bausch and Lomb Spectronic 600 Spectrophotometer.

Gas-liquid chromatography (g.l.c.) was carried out using an Aerograph 202 Gas Chromatograph, with thermal conductivity detectors and a Honeywell-Brown recorder. Stainless steel tubes, 5 ft x 1/4 in, packed with the sup-

ports as stated in the Results section (Table V) were used with helium as the carrier gas.

Refractive indices were measured on a Bausch and Lomb Abbé-3L Refractometer at room temperature.

Solvents

Solvents were used as supplied by the manufacturers unless otherwise stated. Except in the special cases noted, solutions were dried with anhydrous magnesium sulphate. Solvents were removed on a Buchler Flash Evaporator under reduced pressure.

Pyridine

Sodium hydroxide was added to freshly opened bottles of reagent grade pyridine.

Tetrahydrofuran (THF)

THF was distilled from lithium aluminum hydride and stored over molecular sieves.

Dimethyl Sulphoxide (DMSO)

Reagent grade DMSO was stored over molecular sieves.

Drying of t-Butyl Alcohol (79)

Commercial t-butyl alcohol was refluxed over calcium hydride for 1 h then fractionally distilled using a

vigreux column. A middle fraction was collected and stored over molecular sieves overnight. The t-butyl alcohol was decanted from the sieves and fractionally crystallised three times.

Chemical Reagents

Reagents were used as supplied by the manufacturers except where purification procedures have been specified.

Purification of Acrolein and Methyl Vinyl Ketone

Commercial acrolein (methyl vinyl ketone) was distilled under nitrogen in glass-ware that had been washed with chromic acid, then distilled water and dried in an oven at 150°C. A middle fraction was collected in a flask containing hydroquinone.

Purification of Styrene

Commercial styrene was washed three times with sodium hydroxide solution (10%), then washed with saturated sodium chloride solution until free from alkali. The styrene was then dried and distilled through a vigreux column under reduced pressure and an atmosphere of nitrogen. A middle fraction was collected. B.p. 45°C at 17 mm n_D^{25} 1.5441 [b.p. 40°C at 14 mm n_D^{20} 1.5462 (80)].

Purification of p-Toluenesulphonyl Chloride (81)

p-Toluenesulphonyl chloride (10 g) was dissolved in a minimum of chloroform (about 25 ml) and Skelly B (125 ml) added. The precipitate was filtered off and the filtrate evaporated to a small volume. The recrystallised p-toluenesulphonyl chloride (about 7.5 g) was filtered off and dried.

Cleaning of Glass-ware for Use with Styrene Monomer

The glass-ware was cleaned with a mixture of concentrated sulphuric acid and concentrated nitric acid (3:1 on volume), then rinsed several times with distilled water. It was then filled with ammonium hydroxide solution (28%) and left to stand for at least 2 h. After being rinsed with distilled water several times, it was dried in an oven at 140°C.

Literature yields with references and physical data are quoted in [( )].

Coumalic Acid

This was prepared by the method due to Wiley and Smith (33). To powdered malic acid (200 g) and concentrated sulphuric acid (170 ml) were added three 50 ml portions of 30% fuming sulphuric acid at 45 m intervals. The mixture was stirred continuously throughout the reac-

tion period. When the evolution of gas had slackened the mixture was heated on a steam bath for two hours. It was then cooled and poured into crushed ice (800 g), with stirring, and left for 24 h. The precipitate was filtered off, washed thoroughly with 3 x 50 ml ice-cold water and dried in a vacuum oven. The product was used in this state for the preparation of α-pyrone.

Yield 90 g (86%) [80 g (76%) (33)] m.p. 206-9°C [206-9°C (33)](recrystallised).

α-Pyrone XII

The pyrolysis of coumalic acid was carried out according to the method of Zimmerman, Grunewald and Paufler (32). The coumalic acid (30 g) was sublimed at 180-215°C 2-3.5 mm, into a quartz tube, 33 x 2.2 cm, filled with copper turnings and heated at 650-670°C by a Lindberg Hevi-Duty furnace. The sublimation heater was made by winding a Pyrex tube, 40 x 5 cm, with two coils of 24 gauge nichrome wire, 18 ft and 7 ft long, respectively. This tube was fitted with a thermocouple and one end plugged with asbestos. The α-pyrone was collected in two traps, cooled by ice, connected to the exit end of the quartz tube.

Yield 18 g (87.5%) [75% (32)] b.p. 110°C at 40 mm [110° at 26 mm (32)] $\underline{n}_D^{27}$ 1.5276 [$\underline{n}_D^{25}$ 1.5270 (32)]

n.m.r. (82) (CD_3COCD_3) τ 2.4 (m, 2 H), 3.6 (m, 2 H).

endo-5-Formyl-2-oxabicyclo[2.2.2]oct-7-en-3-one, XIII

A mixture of freshly distilled α-pyrone (40 g) and acrolein* (40 g) was stirred for 124 h at 55-60°C. The excess acrolein was removed by rotary evaporation leaving an adduct/α-pyrone mixture (56 g). Based on the acrolein used, the weight of adduct XIII formed was 43.5 g (69%). As the presence of α-pyrone did not seem to adversely affect the reduction of the adduct, and distillation would not completely remove this impurity the product was used without further purification.

n.m.r. (CD_3COCD_3) τ 0.49 (s, 1.0H), 3.6 (m, 2.3 H), 4.75 (m, 1.0 H), 6.9 (m, 0.9 H), 6.5 (m, 0.5 H), 6.9 (m, 1.1 H), 7.8 (m, 2.9 H).

i.r. (neat) 1750 cm^{-1} (C=O).

endo-5-Hydroxymethyl-2-oxabicyclo[2.2.2]oct-7-en-3-one, XIV

To an ice cold solution of XIII (99.5 g) in 50:50 THF: methanol (1700 ml) was added sodium borohydride (17 g) as a suspension in 50:50 THF:methanol (1800 ml) over a period of 1 1/2 h. The mixture was stirred, and cooled in an ice bath, throughout the addition. When the addi-

*Note precautions suggested by Albin (83).

tion was complete the mixture was stirred for a further 10 m, then acetic acid (47 g) was added. To neutralise any excess acetic acid and to dry the solution anhydrous sodium carbonate (60 g) was added. After being vigorously stirred for 30 m the solution was filtered and the solvent evaporated from the filtrate. The resulting slush was extracted with methylene chloride which was then evaporated from the extract leaving a brown oil (100 g). Upon standing for 1-2 days an off-white solid crystallised out. This solid was filtered off, washed with benzene and dried. Yield 27.6 g (35%) m.p. 89-91°C (d) (recrystallised from benzene).

i.r. ($CHCl_3$) 1750 cm^{-1} (C=O), 3450 cm^{-1} (O-H).

n.m.r. ($CDCl_3$) τ 3.5 (m, 2.0 H), 4.85 (m, 1.0 H), 6.35 (m, 1.0 H), 6.65 (t, 1.8 H), 6.95 (s, 1.1 H), 7.7 (m, 1.9 H), 8.9 (q, 1.0 H).

Analysis: Calculated for $C_8H_{10}O_3$ C, 62.32 H, 6.52

Found C, 62.21 H, 6.58

p-Toluenesulphonate, XV

This compound was made by Schleyer's method (46) for the preparation of tosylates. To an ice cold solution of XIV (2 g) in pyridine (30 ml) was added p-toluenesulphonyl chloride (5 g). The mixture was left in a refrigerator overnight then poured into ice/water (300 ml) and

stirred vigorously for 30 m. The water was decanted from the resulting sticky, white solid and a further 300 ml ice/water added. After a further 30 m stirring the product was filtered off as a white powder and dried.
Yield 3.8 g (95%) m.p. 94-95°C (d)
n.m.r. ($CDCl_3$) τ 2.35 (q 4.15 H), 3.6 (m, 2.0 H), 4.78 (m, 1.0 H), 6.3 (m, 3.1 H), 7.5 (s sup. m 4.9 H), 8.8 (m, 1.1 H).

Analysis: Calculated for $C_{15}H_{16}O_5S$ C, 58.42 H, 5.23 S, 10.40

Found C, 58.27 H, 5.26 S, 10.47

endo-5-Chloromethyl-2-oxabicyclo[2.2.2]oct-3-en-7-one, XXI

Compound XXI was prepared by the method of Frazer, et al, (48). To a solution of XIV (1.5 g) in pyridine was added diethyl ether (25 ml). The mixture was cooled in an ice/salt bath and thionyl chloride (0.5 g) added dropwise. The ether was evaporated and a further 0.5 g thionyl chloride added. After being heated for 1 h at 70°C the solution was poured into ice/water and extracted with chloroform. The extract was washed with dilute hydrochloric acid, water and then dried and the solvent evaporated. A crystalline product was obtained.
Yield 1.0 g (60%) m.p. 83-84°C (recrystallised from heptane)

n.m.r. ($CDCl_3$) τ 3.5 (m, 2.0 H), 4.8 (m, 1.0 H), 6.25 (m, 1.0 H), 6.7 (m, 2.05 H), 7.6 (m, 1.95 H), 8.75 (m, 1.05 H).

Analysis: Calculated for $C_8H_9ClO_2$ C, 55.68 H, 5.26 Cl, 20.54

Found C, 55.54 H, 5.16 Cl, 20.38

Methanesulphonate, XXII

Wendler, Slates and Tishler's (51) method was used to prepare XXII. To an ice-cold solution of XIV (0.5 g) in pyridine (7.5 ml) was added methanesulphonyl chloride (1.0 ml). The mixture was left in a refrigerator overnight and then poured into ice/water. Vigorous stirring of this mixture did not produce any solid so the solution was acidified with dilute hydrochloric acid and extracted with chloroform. The extract was washed with water, dried and the solvent evaporated leaving a brown oil.

Yield 0.4 g (54%)

n.m.r. ($CDCl_3$) τ 3.5 (m, 2.1 H), 4.8 (m, 1.0 H), 6.1 (m, 1.9 H), 6.35 (m, 1.25 H), 6.95 (s, 3.0 H), 7.5 (m, 2.0 H), 8.8 (m, 1.1 H).

Reaction of XV with Potassium t-Butoxide

To a solution-suspension of potassium t-butoxide

(2.2 g) in t-butyl alcohol (40 ml, dried over molecular sieves) was added a solution of XV (1.68 g) in benzene (20 ml, sodium dried) and t-butyl alcohol (80 ml). The mixture was vigorously stirred. Aliquots (35 ml) were removed at 1, 5, 16 and 45 m reaction times and acidified with dilute hydrochloric acid. Each acidified portion was extracted with chloroform. Each extract was washed with water, dried and the solvent evaporated leaving a colourless oil. The n.m.r. spectra of the four samples are similar.

Total yield 541 mg (30%)

i.r. ($CHCl_3$) 1710 cm^{-1} (C=O)

n.m.r. ($CDCl_3$) τ 2.4 (q, 4,0 H), 3.45 (s, 2.3 H), 4.15 (m, 2.1 H), 5.9 (m, 2.85 H), 7.0 (m, 0.95 H), 7.55 (s sup. m, 4.0 H), 8.2 (m, 2.1 H).

The above experiment was repeated using XV (173 mg), potassium t-butoxide (324 mg) and t-butyl alcohol (6 ml, purified as described on page 71). The reaction was stopped after 6 m (see Results section).

Yield 74 mg

Elimination Reactions on XV, XXI and XXII

The elimination experiments were carried out under the conditions specified in Table III. At the given reaction time the reaction mixture was poured into water

and extracted with chloroform. The extract was washed with dilute hydrochloric acid, then water, dried and the solvent evaporated.

Reaction of XV with Dimethylamine

A solution of XV (2 g) in dry benzene (30 ml) was poured into a steel bomb and the bomb and contents cooled to -78°C. Dimethylamine (5 ml) was then added, the bomb closed and allowed to warm to room temperature. The reaction mixture was shaken well then heated to 50°C for 24 h. The excess amine was allowed to evaporate, then the solvent was evaporated. The residue was shaken with a mixture of diethyl ether and aqueous sodium bicarbonate. The ether extract was dried and the solvent evaporated leaving an off-white solid (0.6 g), shown by n.m.r. to be starting tosylate. The aqueous bicarbonate extract was further extracted with methylene chloride. The extract was washed with water, dried and the solvent evaporated to leave a yellow oil.

Yield 789 mg (54%)

i.r. ($CHCl_3$) 3320 cm^{-1} (O-H), 1615 cm^{-1} (C=O).

n.m.r. ($CDCl_3$) τ 4.2 (m, 2.0 H), 5.85 (m, 1.0 H), 6.0 (s, 1.0 H), 6.95 (d, 6.2 H), 7.75 (s sup. m, 10.2 H), 8.4 (m, 1.85 H).

α-Bromoacrolein

α-Bromoacrolein was prepared by the method of Baker, et al., (60). To acrolein (1 mole) in cold water (500 ml) was added bromine (1 mole) over a period of 3 h. The mixture was steam-distilled. The lower layer of the distillate was separated off and dried. This was a brown liquid (34 g). The crude product was distilled under reduced pressure and a colourless liquid collected. Yield 22 g (16%) [45% (60)] b.p. 48-50°C at 29 mm [b.p. 46-48°C at 28 mm (60)].

endo-5-Acetyl-2-oxabicyclo[2.2.2]oct-7-en-3-one, XXV

The same procedure was used as for the preparation of XIII, except that the bath temperature was increased to 65°C. α-Pyrone (23 g) and methyl vinyl ketone (17 g) gave a brown oil (39.7 g).

Yield 39. g (99.5%).

n.m.r. ($CDCl_3$) τ 3.5 (m, 2.1 H), 4.7 (m, 1.0 H), 6.1, 6.5, 6.8 (m's, 2.0 H), 7.8 (s sup. m, 4.9 H).

endo-5-(1-Hydroxyethyl)-2-oxabicyclo[2.2.2]oct-7-en-3-one, XXVI

The method used to prepare XXVI was similar to that used for the preparation of XIV. Compound XXV gave a brown oil from which no solid precipitated even on prolonged standing.

Yield 32 g (80%)

i.r. ($CHCl_3$) 3420 cm^{-1} (O-H), 1750 cm^{-1} (C=O)

n.m.r. ($CDCl_3$) τ 3.5 (m, 2.0 H), 4.1 (m, 0.2 H), 4.5 (s, 1.0 H), 4.8 (m, 0.75 H), 6.1 (m, 0.6 H), 6.5 (m, 1.5 H), 7.8 (s sup. m, 3.6 H), 8.8 (pair d sup. m 4.0 H).

p-Toluenesulphonate XXVII

A method of preparation similar to that of the preparation of XV was used. Compound XXVI (10.8 g) gave an oil (10.7 g). An off-white solid (4.2 g) separated from this oil after it had been refluxed with diethyl ether for about 30 m.

Yield 4.2 g (20%) m.p. 115°C (d) (recrystallised from benzene/Skelly B)

i.r. ($CHCl_3$) 1750 cm^{-1} (C=O)

n.m.r. ($CDCl_3$) τ 2.35 (q, 4.0 H), 3.7 (m, 2.0 H), 4.85 (m, 1.1 H), 5.8 (m, 0.9 H), 6.35 (m, 1.1 H), 7.5 and 7.65 (s sup. m, 5.0 H), 8.75 (d sup. m, 3.9 H).

Analysis: Calculated for $C_{16}H_{18}O_5S$ C, 59.61 H, 5.63 S, 9.94

Found; C, 59.33 H, 5.73 S, 9.68

Elimination Experiments on XXVII

These experiments were carried out under the conditions specified in Table IV. A similar workup procedure was used as for the elimination experiments on XV,

XXI and XXII. The residual oil was taken up in a small quantity of chloroform and Skelly B added to the solution until no more starting tosylate XXVII was precipitated. The tosylate was filtered off and the solvent evaporated from the filtrate to give the product A.

n.m.r. ($CDCl_3$) τ 3.5 (t sup. m, 2.0 H), 4.8 (broad m, 2.5 H), 5.7 (t, 0.5 H), 6.4 (m, 0.5 H), 7.1 (m, 0.5 H), 7.3 (m, 1.0 H), 7.6 (m, 0.9 H), 7.8 (m, 0.4 H), 8.3 (pair t sup. broad m, 2.5 H), 8.8 (m, 0.9 H).

Polymerisation of Styrene

Accurately weighed samples of freshly distilled styrene (∿5 g) were placed in ampoules (some with a pre-weighed quantity of A), degassed by three freeze-thaw cycles, and the ampoules sealed under vacuum. The ampoules were then placed in a water bath at the required temperature for a given length of time (see Table VI). The ampoules were then cooled in a Dry Ice-acetone bath and opened. Each sample was poured into ethanol (50 ml), stirred well and left to stand for 4 h. The precipitated polymer was filtered off and dissolved in benzene (50 ml). Methanol (50 ml) was added, with stirring, to the solution and the mixture left for 4 h. The polymer was again filtered off and the process repeated. The resulting polymer was dried and weighed.

Structure Determination of XIV

To a stirred solution of XIV (2.0 g) in ethanol (16 ml) and liquid ammonia (100 ml) was added sodium (1.0 g) in small pieces. When the blue colour had discharged ammonium chloride (2.2 g) was added and the ammonia was allowed to evaporate. The remaining solution was poured into ice/water (100 ml) then acidified with dilute hydrochloric acid. The solvent was evaporated and the residue extracted with diethyl ether. The extract was washed with aqueous sodium bicarbonate, water, then dried and the solvent evaporated to give XIX. The bicarbonate washings were acidified, the solvent evaporated and the residue extracted with diethyl ether. The extract was dried and the ether evaporated leaving an oil, XVIII (1.29 g (64%)). This oil was hydrogenated (155 ml of hydrogen absorbed) in methanol (25 ml) using 5% palladium on charcoal (75 mg), giving another oil, XX (1.28 g (98%)). A portion of this oil (453 mg) was dissolved in an aqueous sodium hydroxide solution (slight excess) and sodium carbonate added (0.1 g). The solution was rapidly stirred and a solution of potassium permanganate (1.0 g) in water (50 ml) added to it dropwise over 3 h. When the addition was complete the reaction flask was placed in an ice bath and the mixture vigorously stirred for a further 16 h, during which time the bath was allowed to warm up to room temperature. The

reaction mixture was heated on a steam bath for a few minutes, then the manganese dioxide filtered off. The filtrate was acidified with dilute hydrochloric acid and the solvent evaporated. The residue was extracted with diethyl ether. The extract was dried and the ether evaporated leaving a white solid.

Yield 310 mg (66%) m.p. 195-203°C. After recrystallisation from water m.p. 228-230°C.

Mixed m.p. with recrystallised commercial trans-1,2-cyclohexanedicarboxylic acid, 228-229.5°C.

Yield of XIX 280 mg (15%) m.p. 95-97°C.

i.r. ($CHCl_3$) 1750 cm^{-1} (C=O)

n.m.r. (CD_3COCD_3) τ 4.25 (m, 2.0 H), 5.8 (m, 2.1 H), 7.8 (m, 6.2 H).

trans-1,2-Cyclohexanedicarboxylic Anhydride

A mixture of trans-1,2-cyclohexanedicarboxylic acid (3.0 g) and acetyl chloride (30 ml) was refluxed until a clear solution was obtained. The solution was cooled in ice upon which a mass of crystals formed. The crystals were filtered off and washed with a small quantity of diethyl ether.

Yield 2.1 g (78%) m.p. 147-150°C [145-146°C (80)].

trans-2-Acetylcyclohexanecarboxylic Acid

To a solution of dimethyl cadmium in diethyl

ether, prepared by the method of Gilman and Nelson (84) from magnesium (0.73 g), methyl bromide (3.8 g) and cadmium chloride (3.1 g), was added trans-1,2-cyclohexanedicarboxylic anhydride (2.1 g) in small quantities over a period of 20 m. The reaction mixture was cooled during the addition. The mixture was then refluxed for 1 h and hydrolysed with 10% sulphuric acid. The ether layer was separated and extracted with aqueous sodium bicarbonate. This extract was acidified with dilute hydrochloric acid and extracted several times with chloroform. The chloroform extracts were dried and the solvent evaporated leaving an oil which crystallised on standing.

Yield 1.62 g (70%) m.p. 130-132°C (recrystallised from ethyl acetate/heptane).

2,4-Dinitrophenylhydrazone m.p. 194-197°C

n.m.r. ($CDCl_3$) τ 2.3 (s, 1.0 H), 7.3 (m, 2.0 H), 7.8 and 8.0 (s sup. m, 6.0 H), 8.7 (m, 4.9 H).

Analysis: Calculated for $C_9H_{14}O_3$ C, 63.52 H, 8.28

Found C, 63.00, 63.09, 63.07

H, 8.55, 8.33, 8.07

trans-1,2-Cyclohexanedicarboxylic Acid from trans-2-Acetylcyclohexanecarboxylic Acid.

A pellet of sodium hydroxide was dissolved in 5% sodium hypochlorite solution (7 ml Javex). To this solu-

tion was added trans-2-acetylcyclohexanecarboxylic acid (167 mg) and the mixture cooled by a cold water bath and stirred for 1 h. A solution of sodium bisulphite (0.1 g) in water (5 ml) was then added and the mixture acidified with dilute hydrochloric acid. The product started to precipitate almost immediately and was filtered off after a few minutes.

Yield 109 mg (65%) m.p. 228-230°C [228-230°C (85)]

Mixed m.p. with authentic trans-1,2-cyclohexanedicarboxylic acid, 226-228°C.

Decarboxylation of XIV

Compound XIV (687 mg) was heated to 140°C under reduced pressure (~2.5 mm) for 1 h. The volatile material was collected in a cold trap at -78°C.

Yield 360 mg (74%) $\underline{n}_D^{25.5}$ 1.5111.

u.v. (95% ethanol) λ_{max} 259 mμ (log ε 3.67)

n.m.r. ($CDCl_3$) τ 4.15 (m, 4.0 H), 6.45 (d, 2.0 H), 7.3 (s, 1.2 H), 7.8 (m, 2.8 H).

Tetracyanoethylene Adduct of XXXII

A small quantity of XXXII was dissolved in benzene and an equivalent amount of TCNE added. When the bright orange colour of the reaction mixture had faded to a pale yellowish green colour the solvent was evaporated leaving a yellow solid. The solid was recrystallised three

times from benzene/Skelly B (giving an almost white solid) and dried.

m.p. 177-178°C.

n.m.r. (CD_3COCD_3) τ 3.35 (m, 1.9 H), 6.1 (m, 2.2 H), 6.7 (m, 2.0 H), 7.35 (s, 1.0 H), 7.6 (m, 1.4 H), 9.0 (m, 1.6 H).

Analysis: Calculated for $C_{13}H_{10}N_4O$ C, 65.52 H, 4.32 N, 23.52

Found C, 65.35 H, 4.37 N, 22.49

Decarboxylation of XXV

Compound XXV (2.0 g) was heated to 140°C under reduced pressure (∿2.5 mm) for 90 m. The volatile material was collected in a cold trap at -78°C.

Yield 1.2 g (75%)

i.r. (neat) 1710 cm^{-1} (C=O),

u.v. (95% ethanol) λ_{max} 264 mμ (log ε 3.12)

n.m.r. ($CDCl_3$) τ 4.15 (m, 4.0 H), 6.9 (m, 1.2 H), 7.6 (m, 2.0 H), 7.8 (s, 3.0 H).

Tetracyanoethylene Adduct of XXXIV

Compound XXXIV (∿0.5 g, containing α-pyrone as an impurity) was placed on a silica gel (∿50 g) column and eluted with 2:5 diethyl ether:Skelly B. After 150 ml of solvent had eluted the eluent was collected until 150 ml was obtained. The solvent was evaporated leaving 250 mg of oil. This oil was treated with TCNE in a manner simi-

lar to that described for the preparation of the TCNE adduct of XXXII. Recrystallisation of the solid product from benzene/Skelly B gave an almost white solid.

m.p. 200°C.

n.m.r. (CD_3COCD_3) τ 3.3 (m, 1.9 H), 5.6 (m, 1.0 H), 6.0 (m, 1.0 H), 6.6 (m, 1.05 H), 7.5 (m, 1.2 H) adjacent to 7.7 (s, 3.3 H), immediate upfield region obscured by solvent absorption peaks.

Analysis: Calculated for $C_{14}H_{10}N_4O$ C, 67.20 H, 4.02 N, 22.39

Found C, 67.24 H, 3.82 N, 22.10

Kinetics of Decarboxylation of XIV and A

A standard, mercury filled, hydrogenation apparatus was utilised for the kinetic runs, as only approximate data were required. A three-necked, 50 ml, round-bottomed flask was fitted with a thermometer and a rubber serum cap. A magnetic stirring bar and ethyl benzoate (25 ml) were placed in the flask which was then attached to the hydrogenation apparatus. The system was flushed with nitrogen three times. The flask was then immersed in an oil bath, at the required temperature, to the level of the solvent in the flask. The oil in the bath and the solvent in the reaction flask were magnetically stirred and the system allowed to come to equilibrium. The bath tem-

perature was not allowed to vary by more than ±1°C. When the system had attained equilibrium the pressure was adjusted to atmospheric and gas burette reading noted. A sample of the compound being studied (approximately 200 mg), in ethyl benzoate (1ml), was injected into the flask. Readings of the gas burette were taken at convenient intervals until carbon dioxide was no longer evolved. The V_∞ reading was taken several hours after carbon dioxide evolution ceased. The appropriate rate expressions and rate data are given in the Results section.

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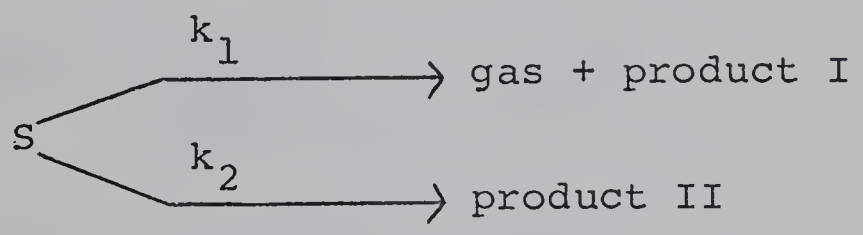
APPENDIX

In cases where a compound is reacting by two different first-order pathways, only one of which involves the formation of a product which is measured eq [16] does not hold. Considering the following situation, where the product measured is a gas,



The rate of disappearance of S is given by

$$\frac{-d[S]}{dt} = (k_1 + k_2)[S] = k[S]$$

Therefore, $\ln([S_o]/[S]) = kt$

Therefore, $[S] = [S_o]e^{-kt}$

The rate of appearance of gas is given by

$$\frac{d[gas]}{dt} = k_1[S]$$

$$= k_1[S_o]e^{-kt}$$

Therefore $[gas] = k_1[S_o]\int_{t=0}^{t=t} e^{-kt}\,dt$

$$= k_1[S_o]\left[\frac{e^{-kt}}{-k}\right]_{t=0}^{t=t}$$

$$= \frac{-k_1}{k}[S_o](e^{-kt}-e^{\circ})$$

$$= \frac{-k_1}{k}[S_o](e^{-kt}-1)$$

Therefore $\frac{[gas]k}{k_1[S_o]} = 1 - e^{-kt}$

Therefore $1- \frac{[gas]k}{k_1[S_o]} = e^{-kt}$

[22] Therefore $\ln(1-\frac{[gas]k}{k_1[S_o]}) = -kt$

Now $k = k_1 + k_2$

and $\frac{k_1}{k_2} = \frac{V_\infty}{V_T} \Big/ \left(1- \frac{V_\infty}{V_T}\right)$

where $\frac{k_1}{k_2}$ = ratio of products from path 1 to products from path 2.

V_∞ = volume of gas evolved to $t = \infty$

V_T = theoretical value of V_∞ if all S reacts via path 1

$$\text{Therefore} \quad k = k_1 + k_1\left(\left(1 - \frac{V_\infty}{V_T}\right)\Big/\frac{V_\infty}{V_T}\right)$$

$$= k_1\left(1 + \left(\left(1 - \frac{V_\infty}{V_T}\right)\Big/\frac{V_\infty}{V_T}\right)\right)$$

$$\text{Let} \quad F = 1 + \left(\left(1 - \frac{V_\infty}{V_T}\right)\Big/\frac{V_\infty}{V_T}\right)$$

Substituting in [22] we get

$$\ln\left(1 - \frac{[\text{gas}]k}{[S_o]k/F}\right) = -kt$$

$$[23] \qquad -k = \frac{1}{t}\ln\left(\frac{[S_o] - [\text{gas}]F}{[S_o]}\right)$$

Given that $[S_o]$ would give V_T if S reacted only via path 1 we can substitute V_T for $[S_o]$ in [23]. Also [gas] is given by V_t. This gives,

$$[17] \qquad -k = \frac{1}{t}\ln\left(\frac{V_T - V_tF}{V_T}\right)$$